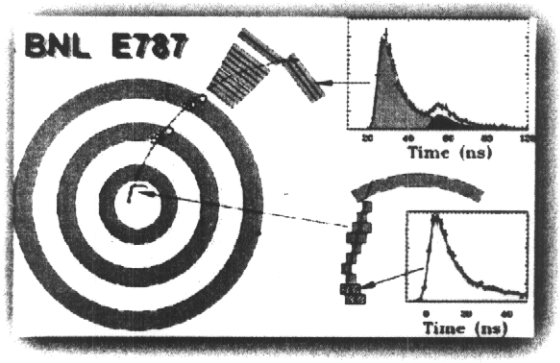


La-Thuile
March 6, 2002

Rare K-decays and Perspective

- 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

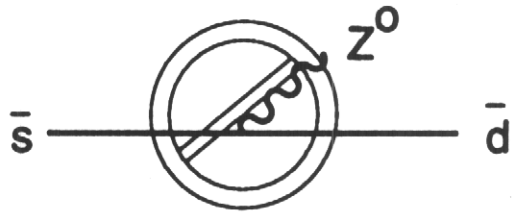
Consequences of Cabibbo - Kobayashi - Maskawa Mixing

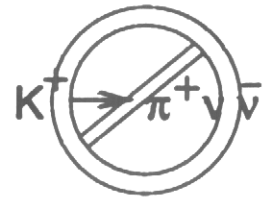
neutral currents:

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

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

No "flavor-changing neutral currents"





Similarly following decays are not allowed

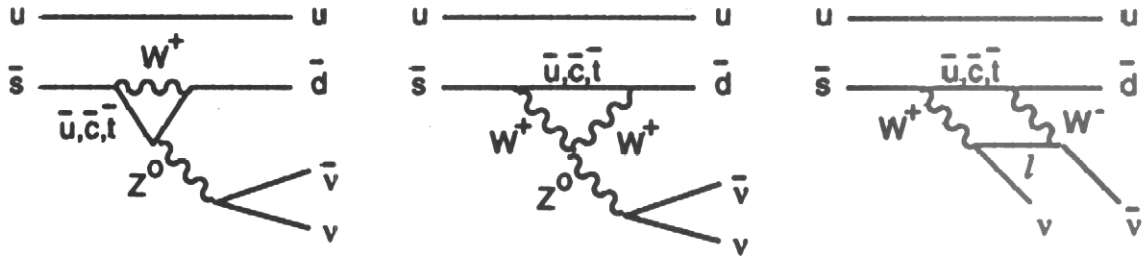
$K_L \to \mu^+\mu^-$

$K_L \to e^+e^-$

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

... 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:

$$\mathrm{BR}_{\mathrm{calc}}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.75 \pm 0.29) \times 10^{-10}$$

A.J. Buras, Preprint hep-ph/0101336

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

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

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

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

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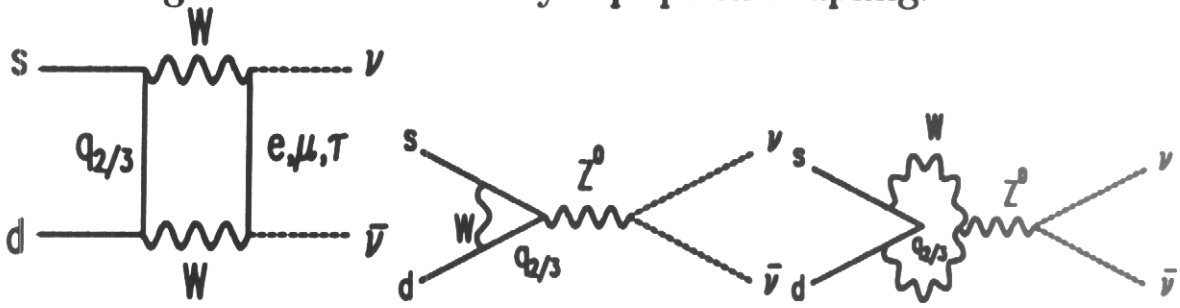
[0]Milind V. Diwan

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

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



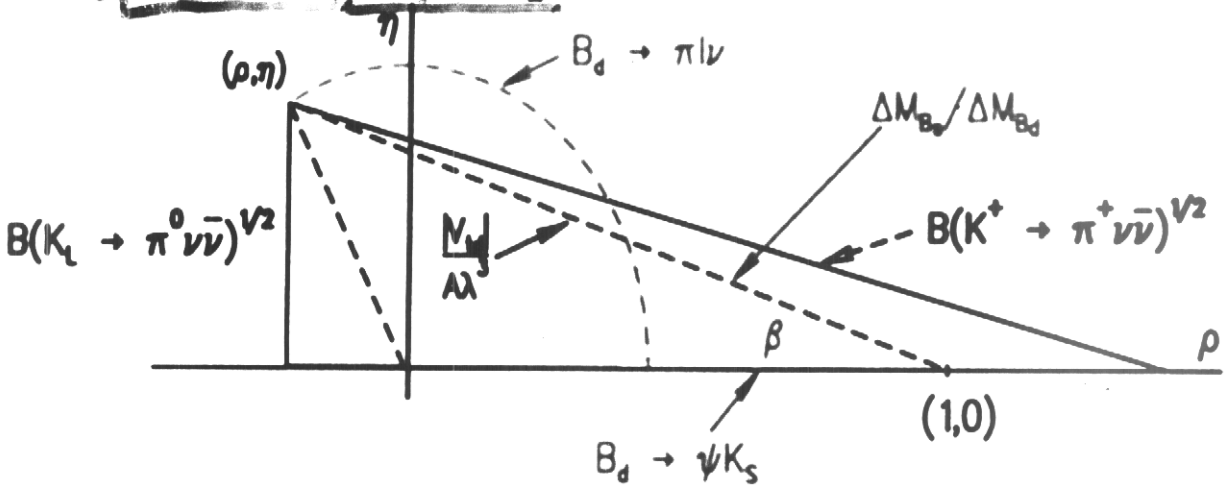
Hadronic matrix element well determined by $K^+ \to \pi^0 e^+ \nu_e$ decay.

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

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

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

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



[0]Milind V. Diwan

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. 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.

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Osaka University

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Princeton University

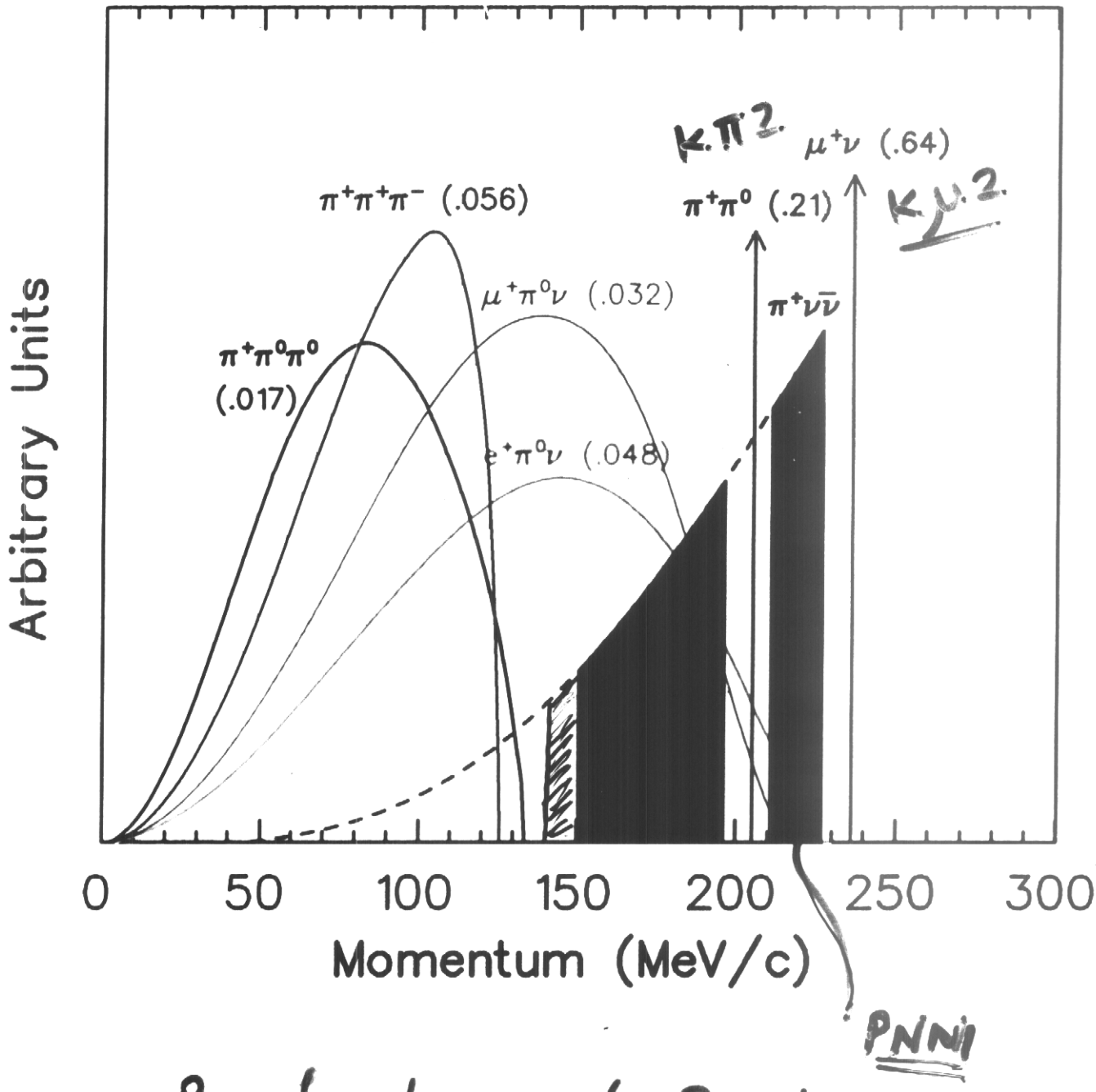
P. Bergbusch, E.W. Blackmore, D.A. Bryman, S. Chen, A. Konaka, J.A. Macdonald, J. Mildenberger, T. Numao, J.-M. Poutissou, and R. Poutissou

TRIUMF

P. Kitching and H-S. Ng

University of Alberta

PNN backgrounds and tools



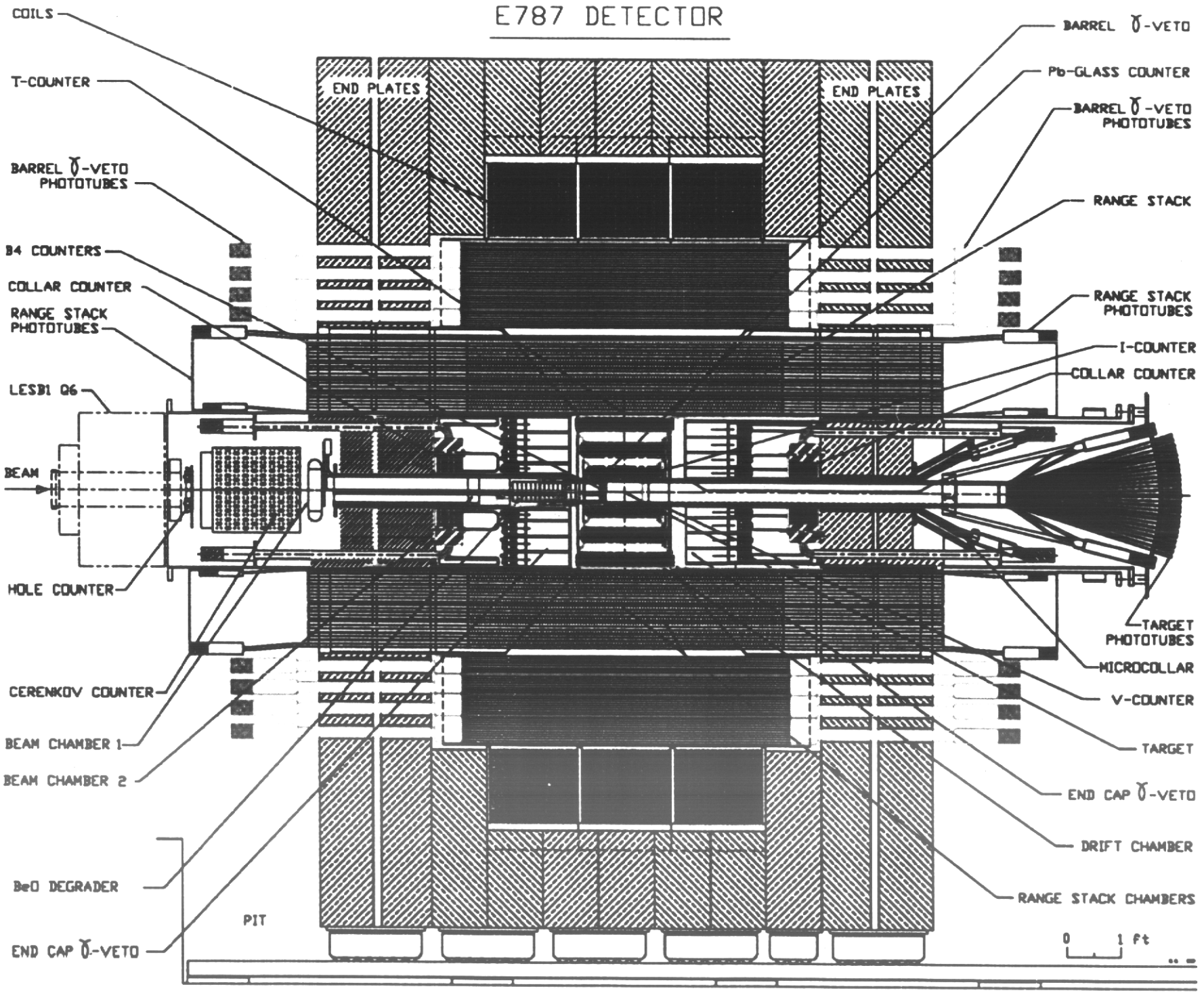
P of charged Particle in decay

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.

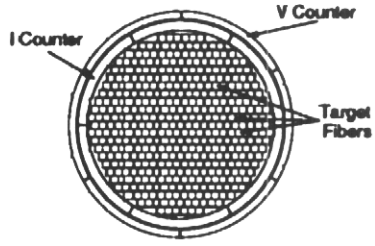
PNN2 main backgrounds

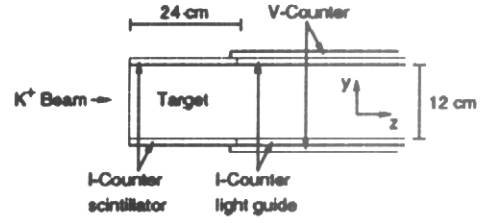
- $K^+ \to \pi^+\pi^0$ with scattering of π^+ in the kaon stopping target: Two body kinematics, Photon veto, and Detection of π^+ scattering in the target.
- $K^+ \to \pi^+\pi^-e^+\nu$: Detection of π^- and e^+ in the target.
- Scattering of π^+ contamination in the beam: K^+ decay time and Cerenkov 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
COILS
T-COUNTER
BARREL γ-VETO PHOTOTUBES
B4 COUNTERS
COLLAR COUNTER
RANGE STACK PHOTOTUBES
LESB1 Q6
BEAM
HOLE COUNTER
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
BeO DEGRADER
END CAP γ-VETO
PIT
END PLATES
END PLATES
BARREL γ-VETO
Pb-GLASS COUNTER
BARREL γ-VETO PHOTOTUBES
RANGE STACK
RANGE STACK PHOTOTUBES
I-COUNTER
COLLAR COUNTER
TARGET PHOTOTUBES
MICROCOLLAR
V-COUNTER
TARGET
END CAP γ-VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0 1 ft

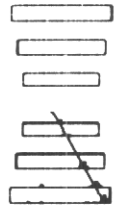
E787 Technique

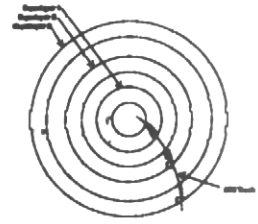
K^+ I.D.'d by beam counters, stop in 400-element sci-fi target



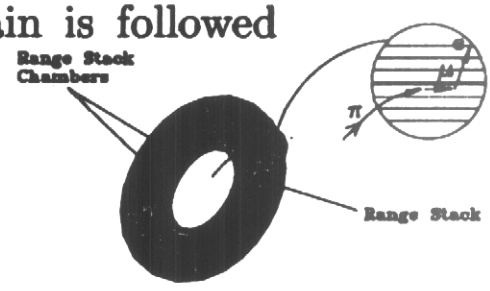


Wait 2ns for decay
Then π^+ tracked & momentum analyzed in UTC (B=1T)

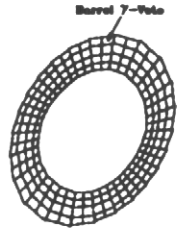


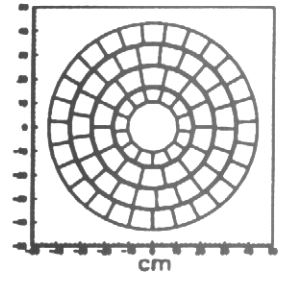


π^+ then ranges out in an Range Stack (scint. + straw ch.)
Range/energy/momentum can be compared.
Also $\pi^+ \to \mu^+ \to e^+$ decay chain is followed

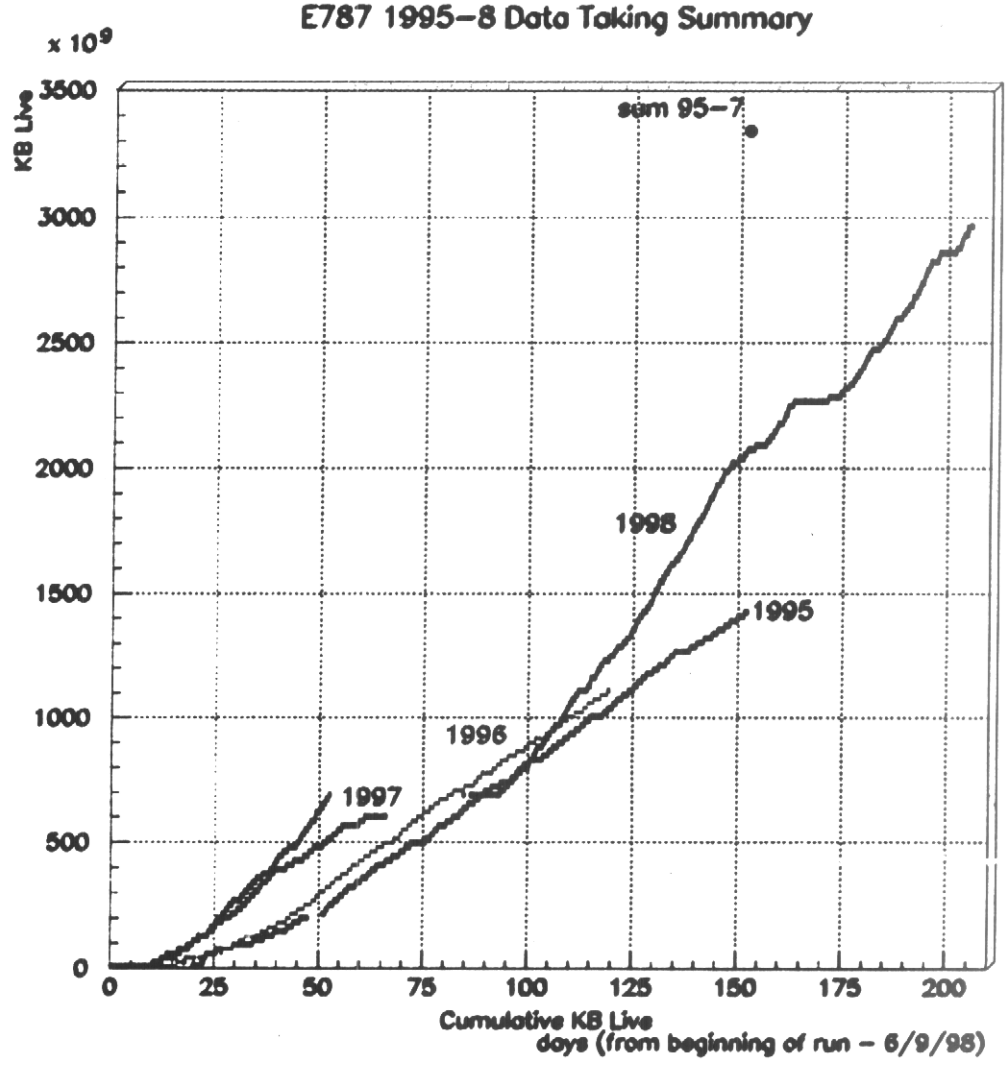


Hermetic photon vetoing via barrel Pb-scint system (BV)
+ CsI-pure endcaps (EC)





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

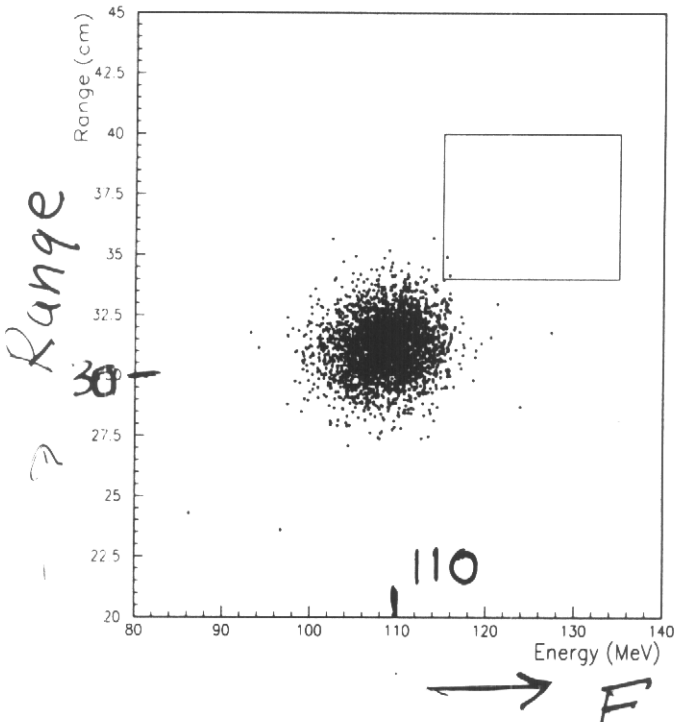
Analysis Technique

- Background measured from data.
  - Measured to $O(10^{-2})$ event level.
  - Two independent 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	$0.066^{0.044}_{-0.025}$

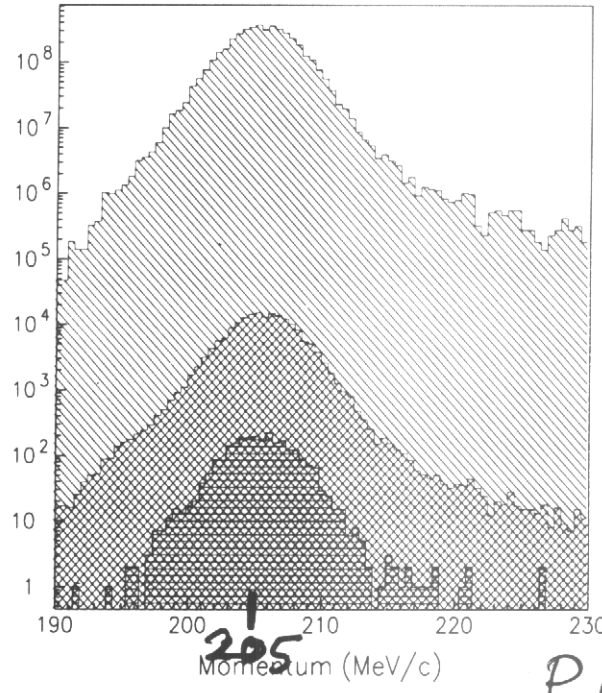
$K_{\pi 2}$ background.

γ veto reversed



N = 2/1.6

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



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

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

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

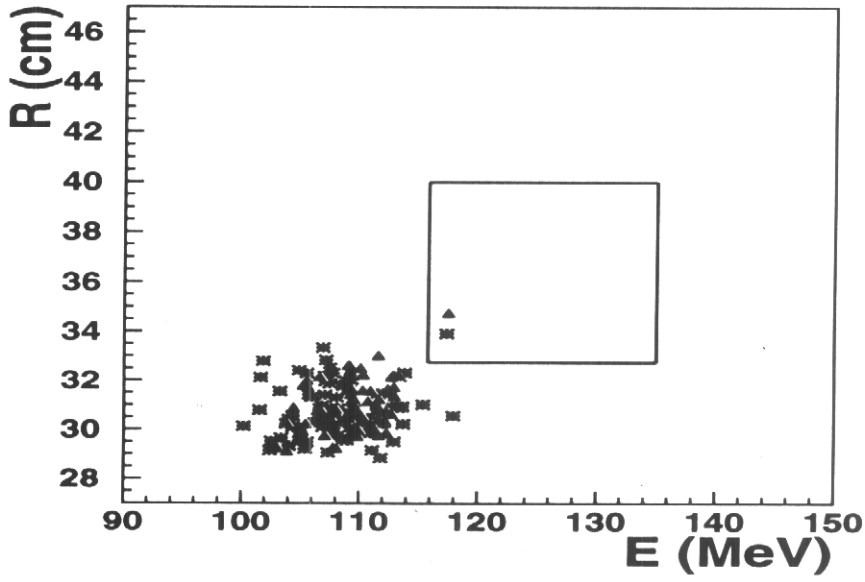
Background	1995–97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam (1 + 2)	0.02 ± 0.02	0.004 ± 0.001
CEX	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total background	0.08 ± 0.02	$0.066^{+0.044}_{-0.025}$

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

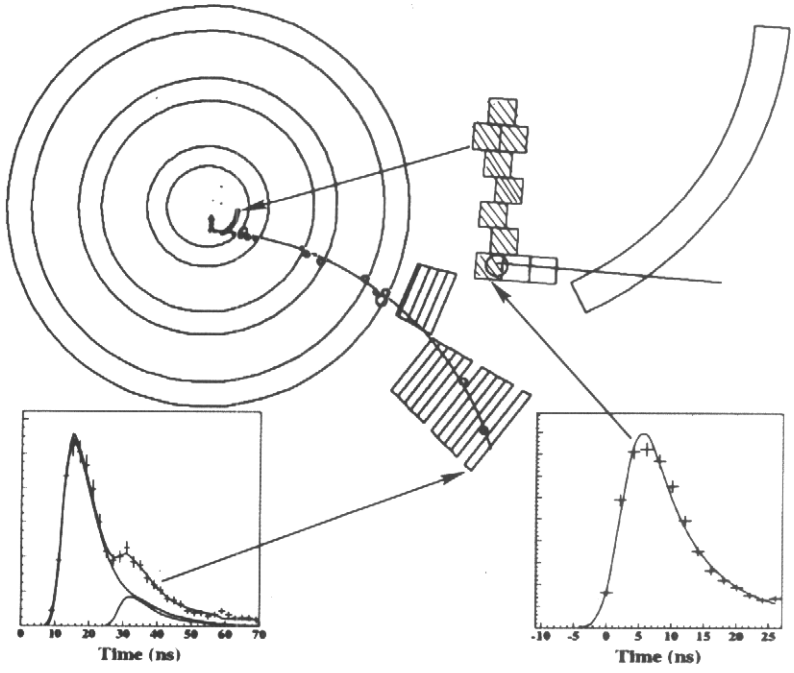
Summary	1995–97	1998
N_K	3.2×10^{12}	2.7×10^{12}
Acc.	0.0021(1)(2)	0.00196(5)(10)
Sensitivity	1.5×10^{-10}	1.89×10^{-10}
Background	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

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

1995–98 Data



Event Display (1998)

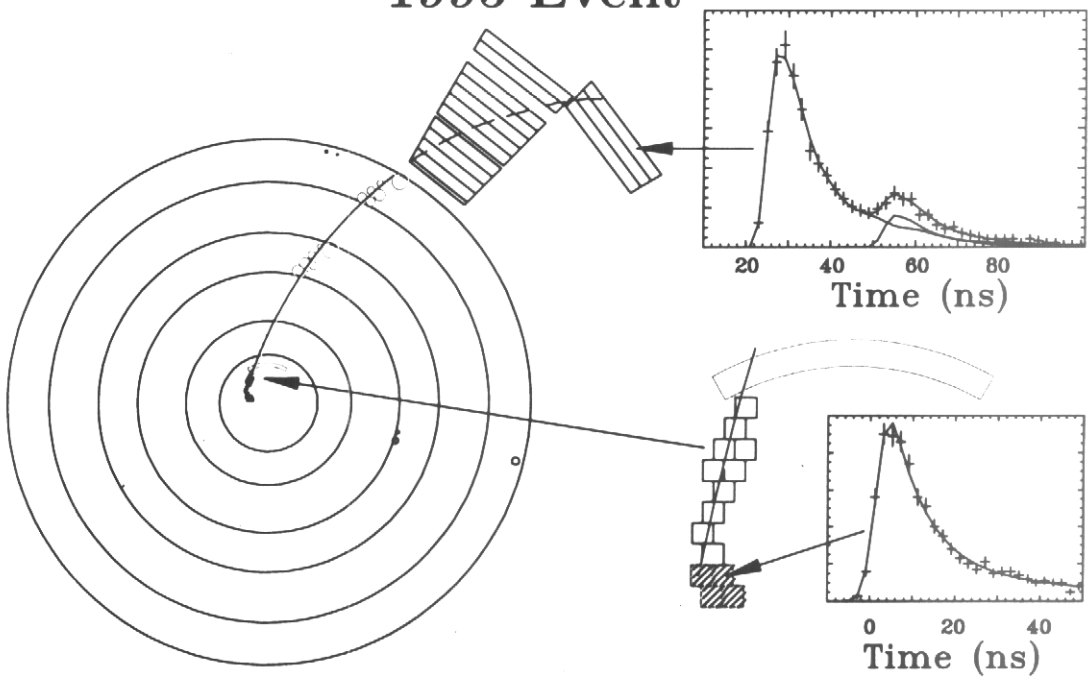


$$\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

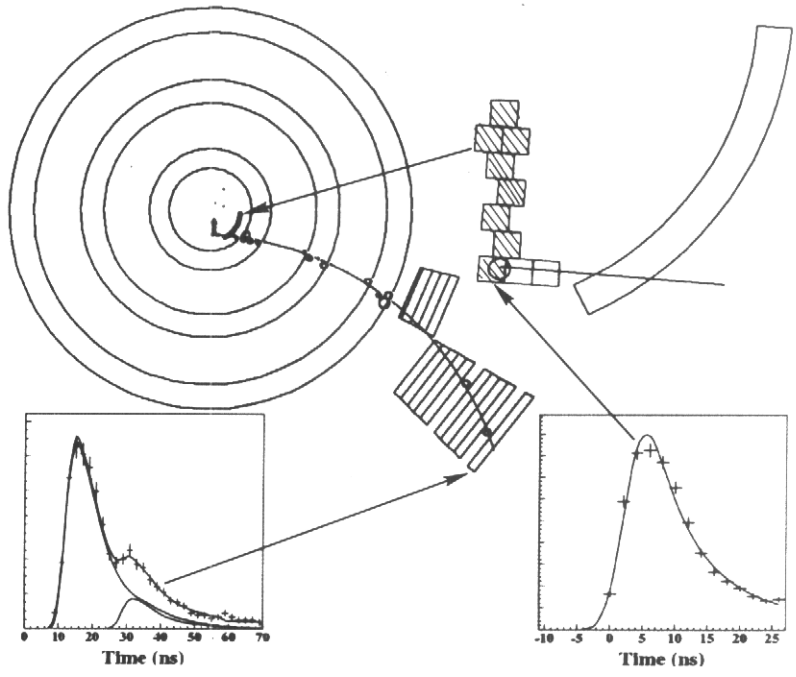
[Lab PR: http://www.bnl.gov/bnlweb/pubaf/pr/2002/bnlpr011002.htm]
[PRL cover: http://ojps.aip.org/prl/covers/88_4.jsp]

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

1995 Event



1998 Event

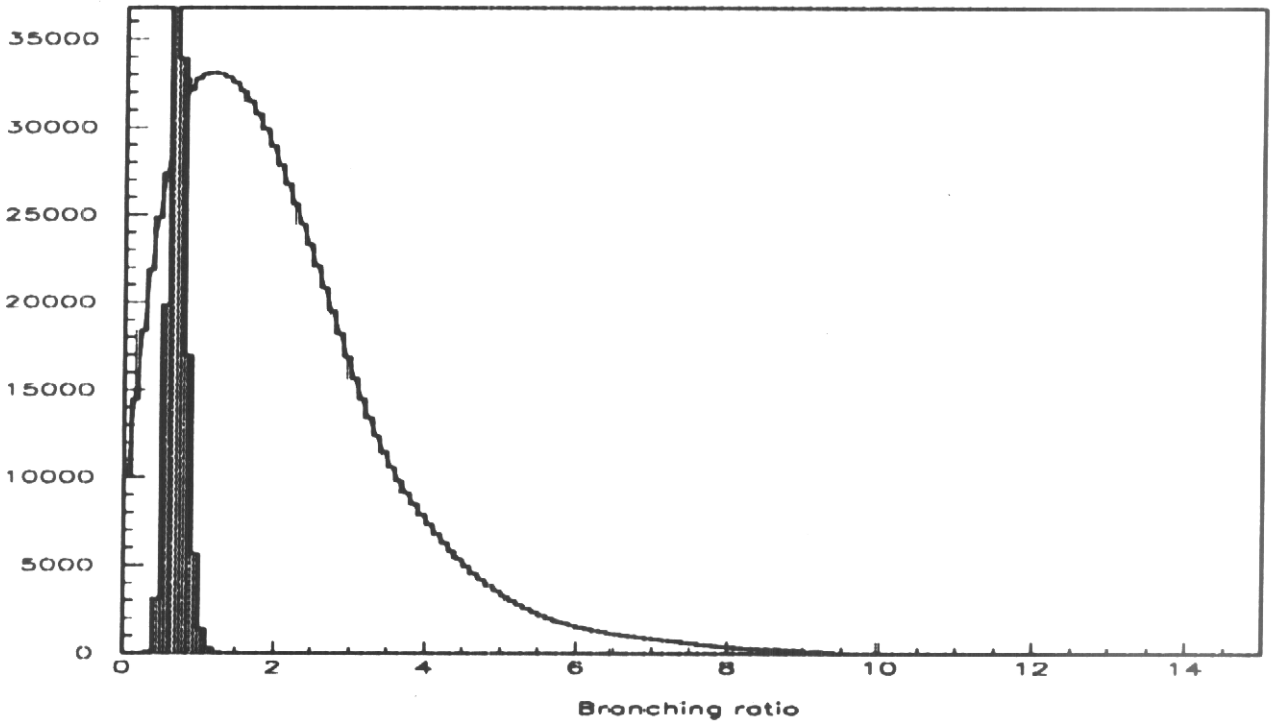


$$\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

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

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

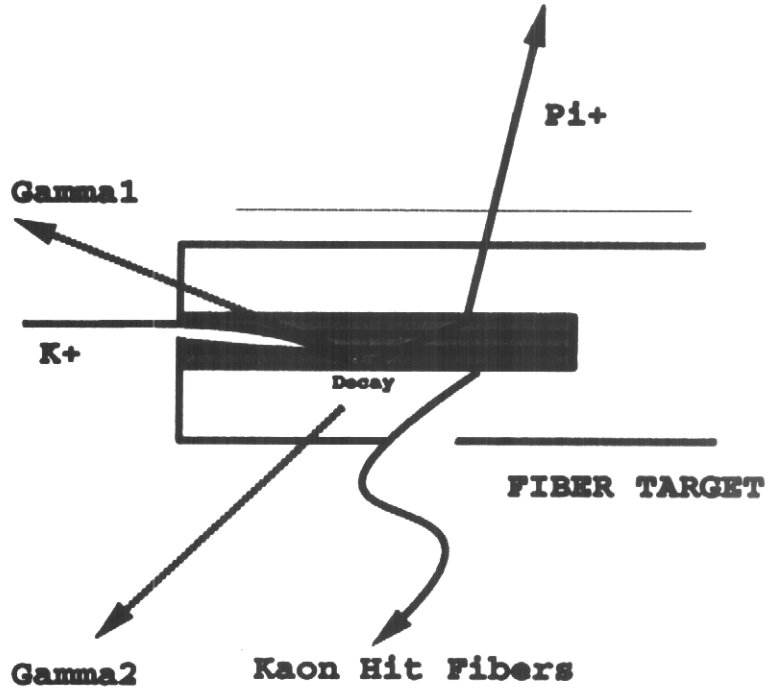
- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- BR($K^+ \to \pi^+ \nu\bar{\nu}$) $= 1.57^{+1.75}_{-0.82} \times 10^{-10}$ (SM: $0.75 \pm 0.29 \times 10^{-10}$)

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]

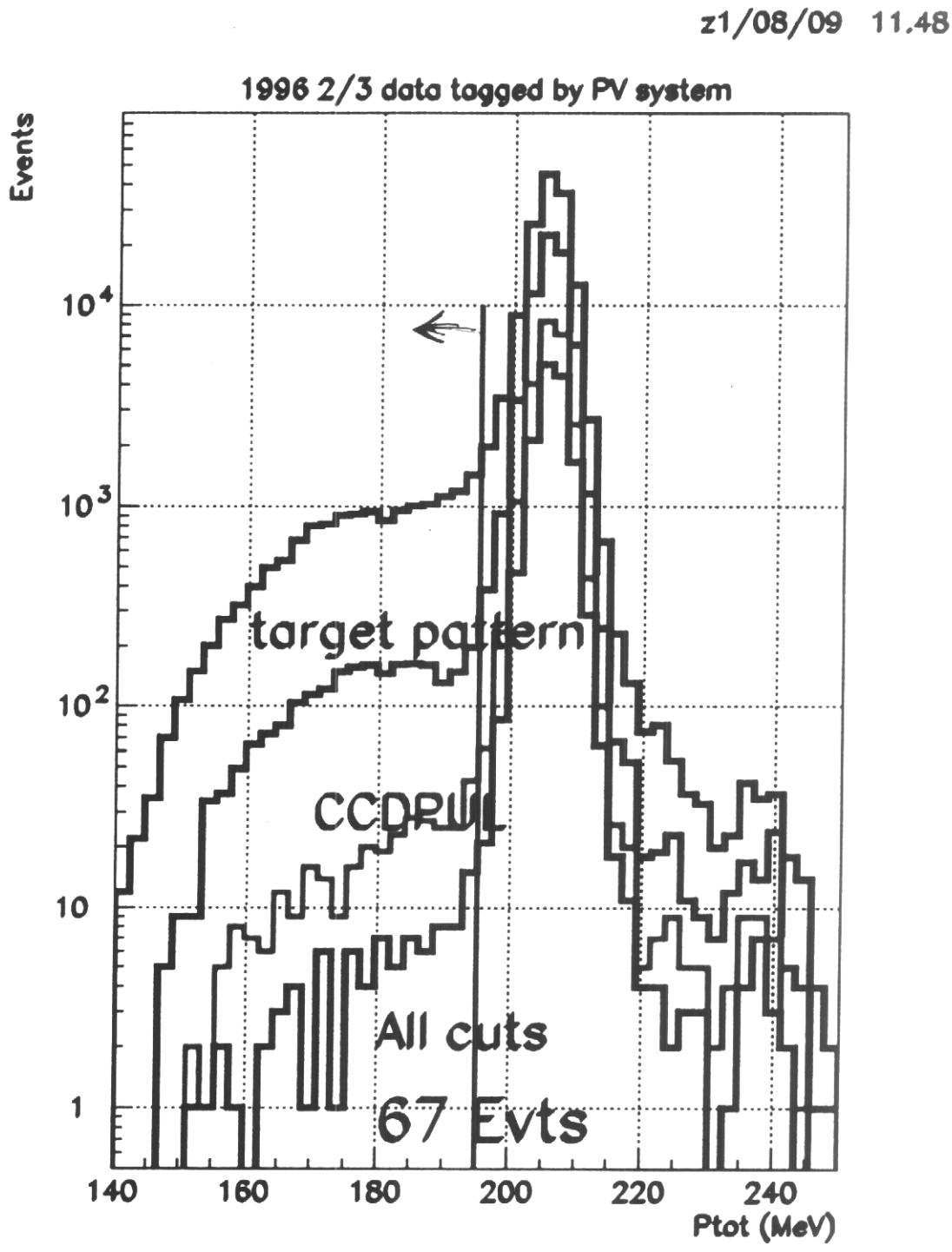
- $P_b \sim 0.02\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% CL)
- already has non-trivial impact on CKM fits [hep-ph/0112135]

PNN2 data analysis

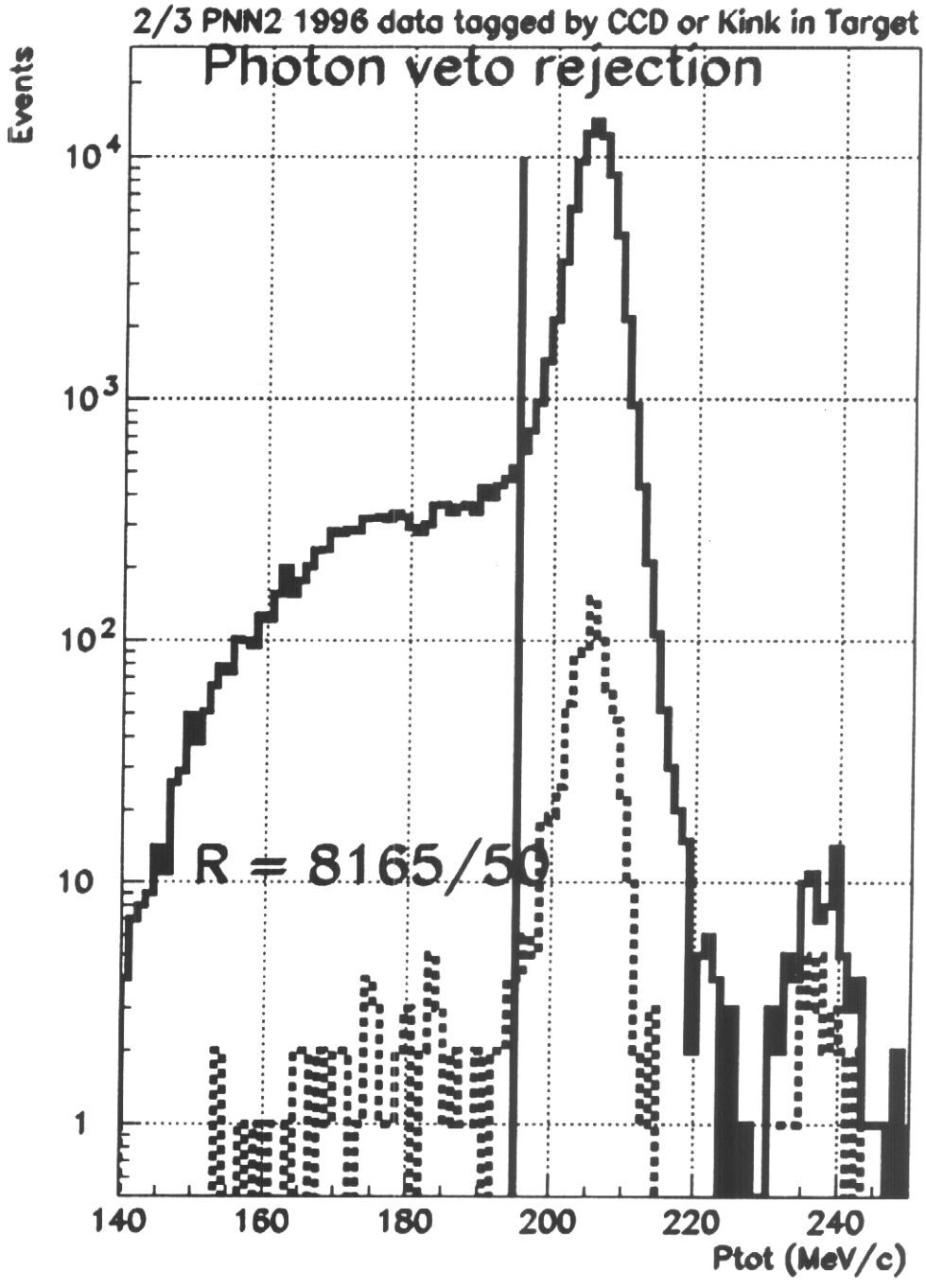
- Good news: Much larger phase space acceptance below Kpi2 peak.
- Bad news: Huge background from $K^+ \to \pi^+\pi^0$ in which π^+ undergoes interaction in the scintillator fiber target.
- Not possible to simulate all details of the main background. Must be measured from data using two independent cuts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



$N = 67$



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

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

PNN2 Final Background Estimate

Table of Backgrounds for PNN2 data

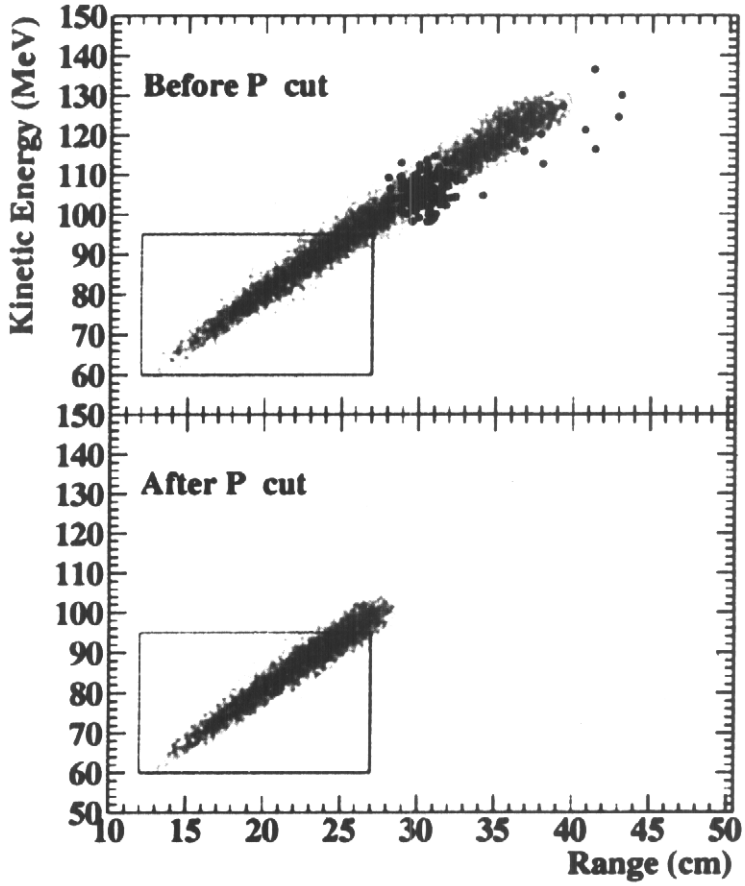
Background	1/3	2/3
KPI2-sct-in-target	0.35 ± 0.12	0.62 ± 0.17
RS-KPI2-sct-in-target	0.004 ± 0.004	0.007 ± 0.006
$K^+ \to \pi^+\pi^0\gamma$	0.021 ± 0.004	0.027 ± 0.004
$K^+ \to \mu^+\nu\gamma$	0.011 ± 0.011	0.007 ± 0.007
1-beam	0.0009 ± 0.0009	0.0003 ± 0.0003
2-beam	0.056 ± 0.056	0.033 ± 0.033
$K^+ \to \pi^+\pi^-e^+\nu$	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 been 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.

Milind V. Diwan



Run 32775 ev 126739

$P = 190.7$ MeV/c $R = 22.0$ cm $E = 86.3$ MeV

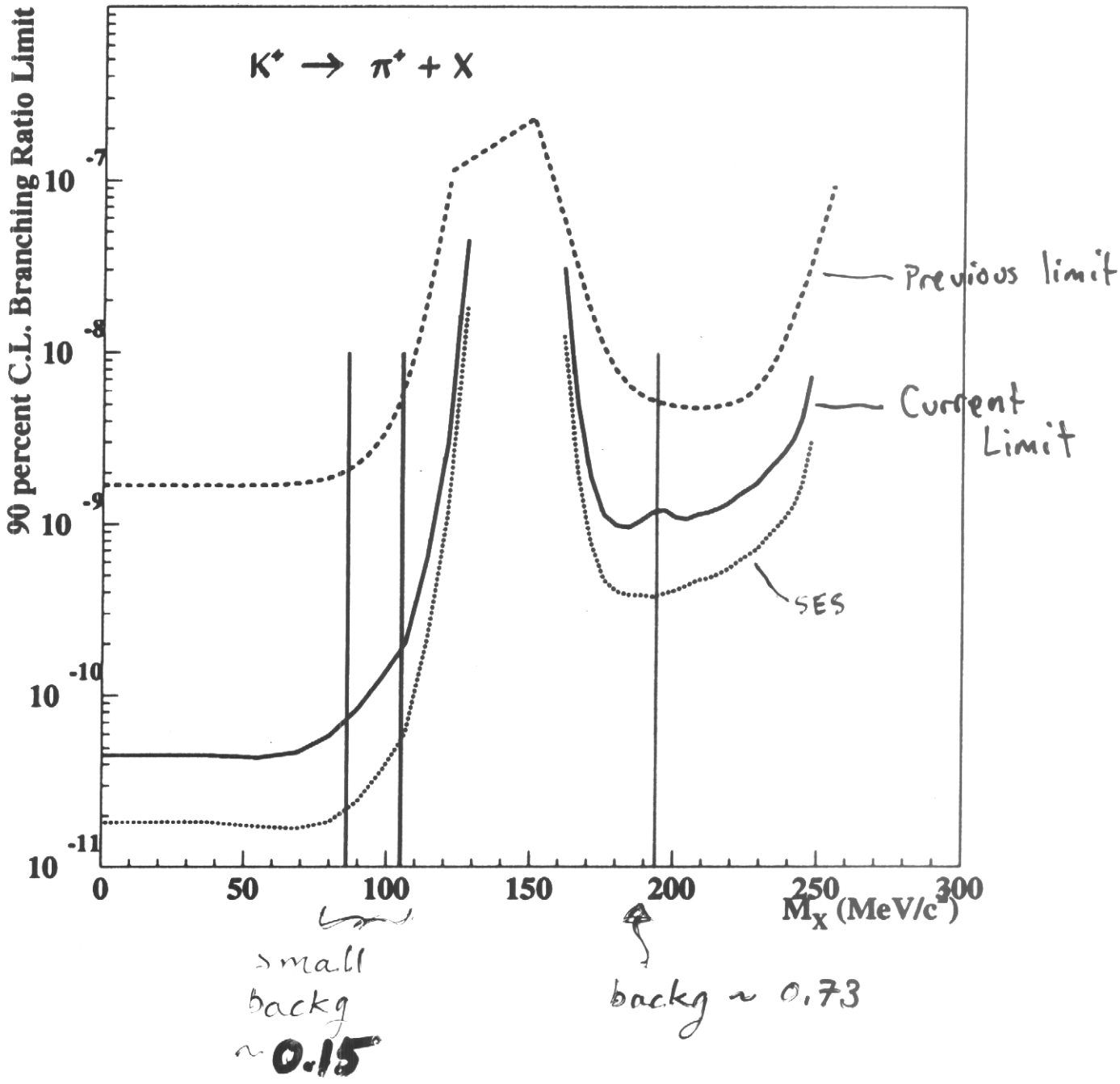
$t_\pi - t_k = 17.7$ ns

Kaon fibers 6

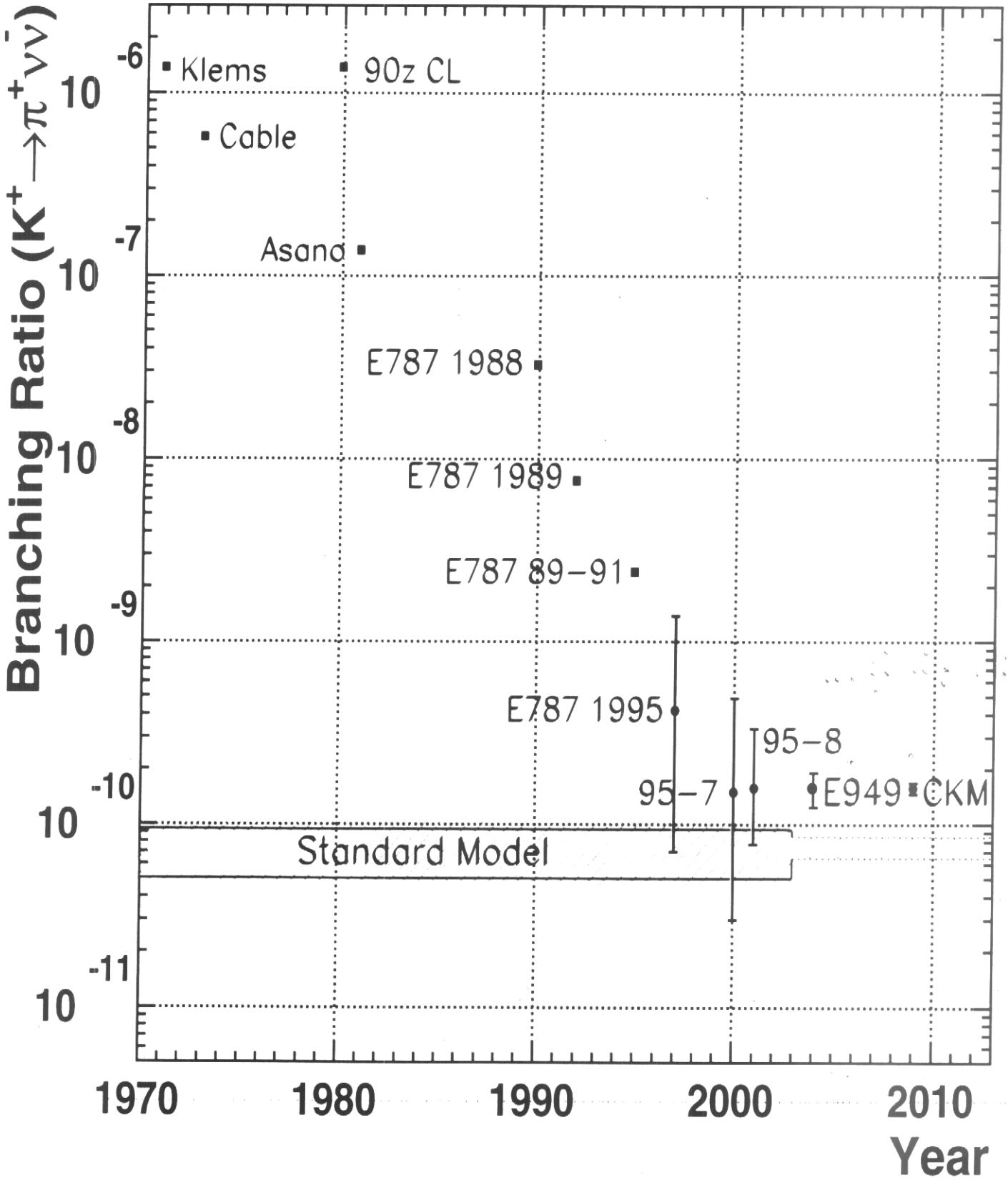
π fibers 4

Txtg 0.1 MeV

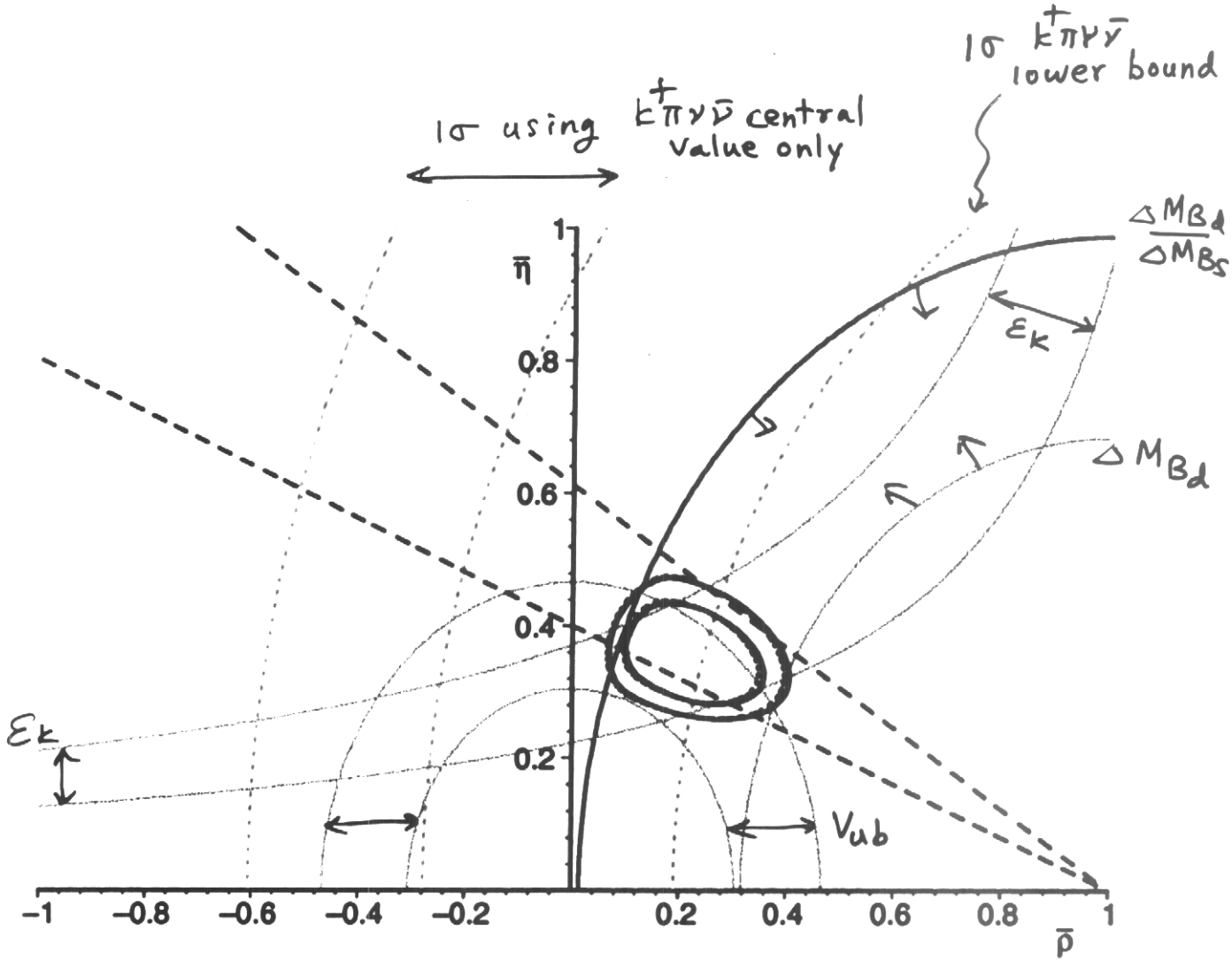
CCD π-ene 0.84 MeV


K⁺ → π⁺ + X
90 percent C.L. Branching Ratio Limit
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
0
50
100
150
200
250
300
M_X (MeV/c²)
Previous limit
Current Limit
SES
small backg ~ 0.15
backg ~ 0.73

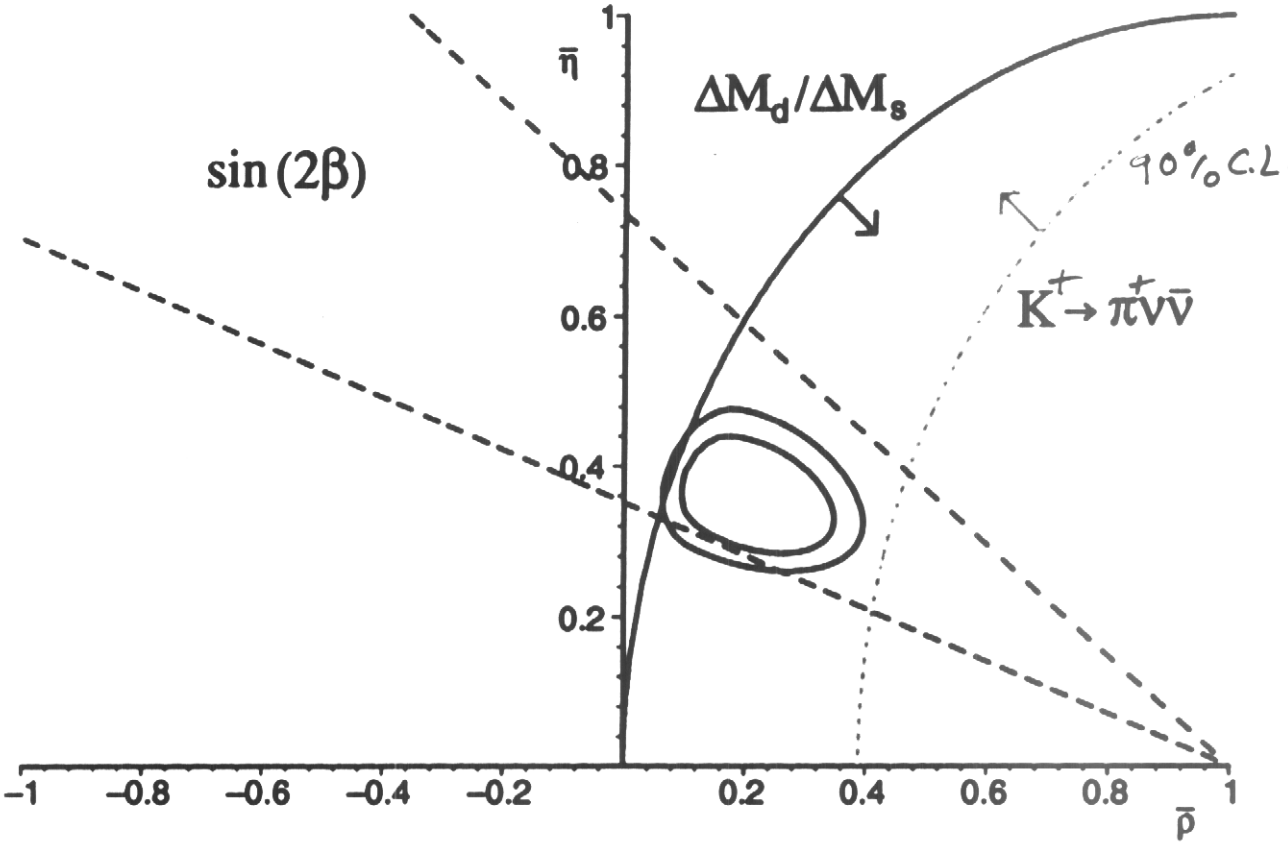
History of the Search for $K^+ \to \pi^+ \nu\bar{\nu}$



$\bar{\rho}$, $\bar{\eta}$ "improved" Wolfenstein variables



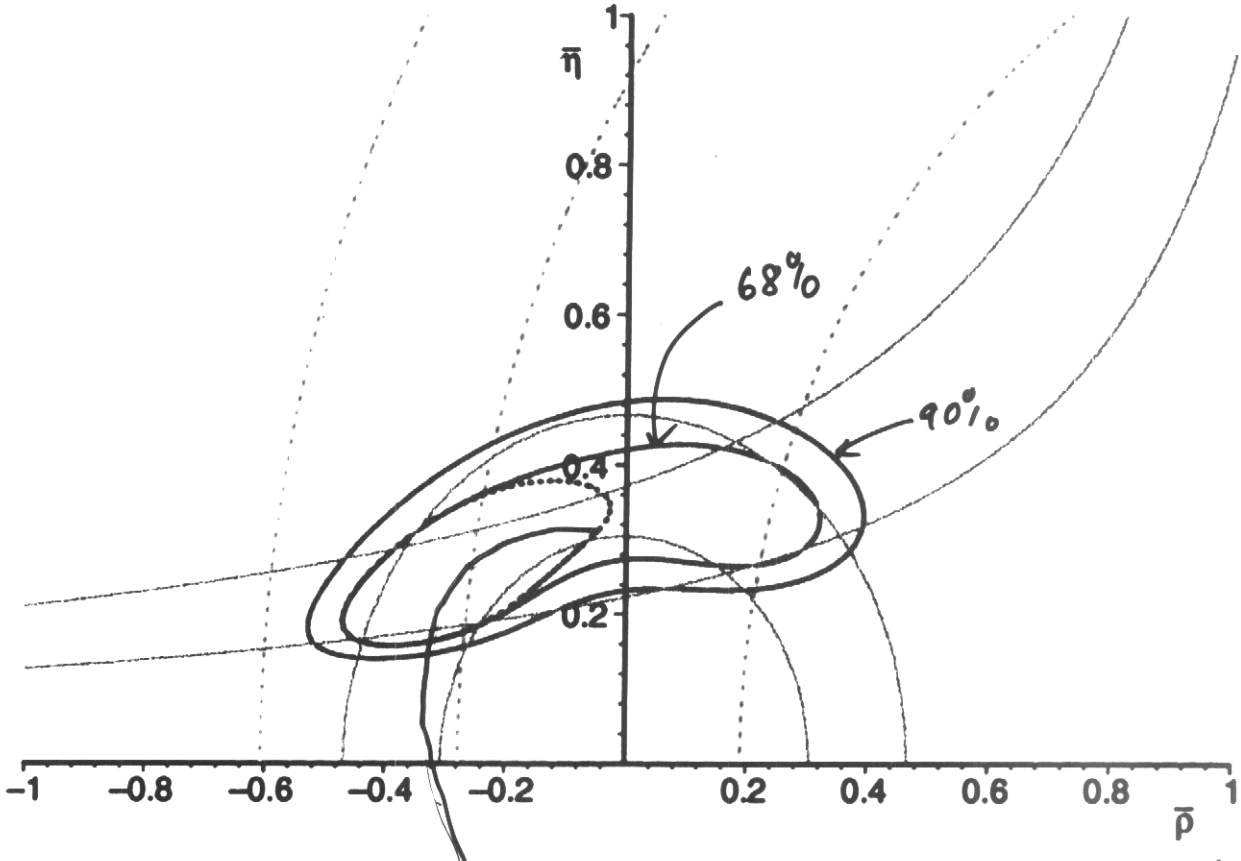
D'Ambrosio + Isidori
2001



hep-ph/ϕ112135 G. D'AMBROSIO & G. ISIDORI

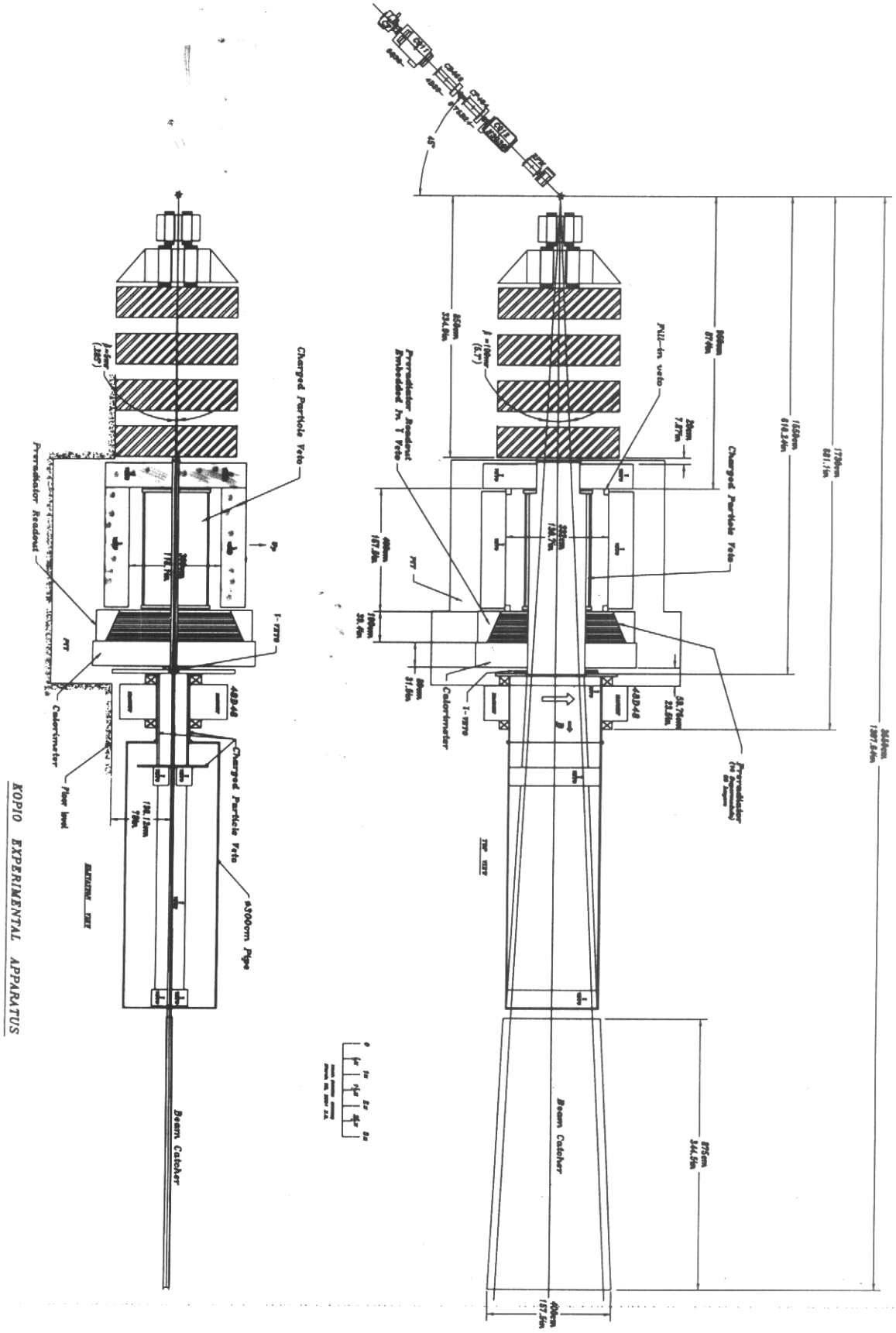
"$K^+ \to \pi^+ \nu\bar{\nu}$: a rising star on the stage of flavour physics"

Fit using $K^+\pi\nu\bar{\nu}$ but no $B_d - \bar{B}_d$ data



Assume x2 better measurement of $K^+\pi\nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$ KOPIO

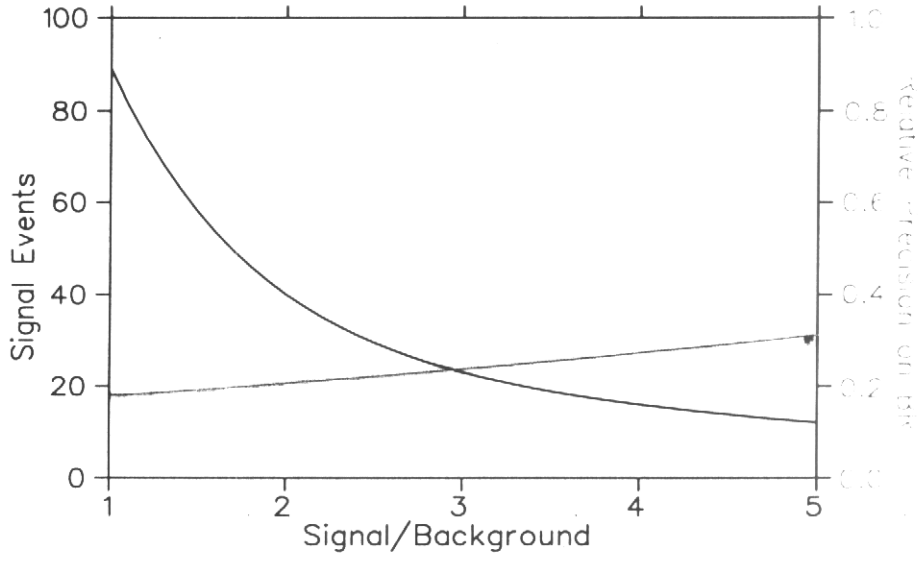


KOPIO EXPERIMENTAL APPARATUS

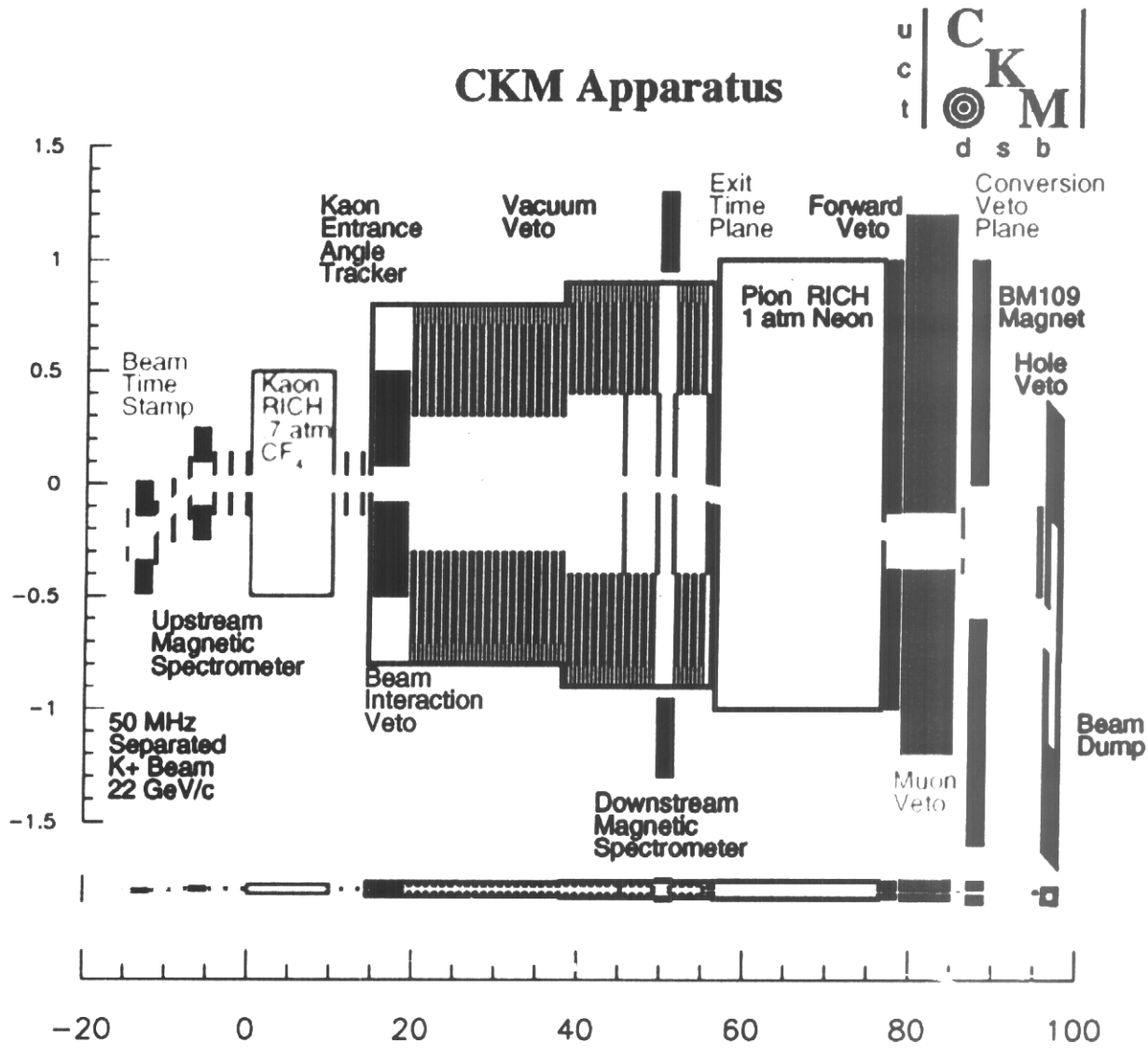
KOPIO Signal and Backgrounds

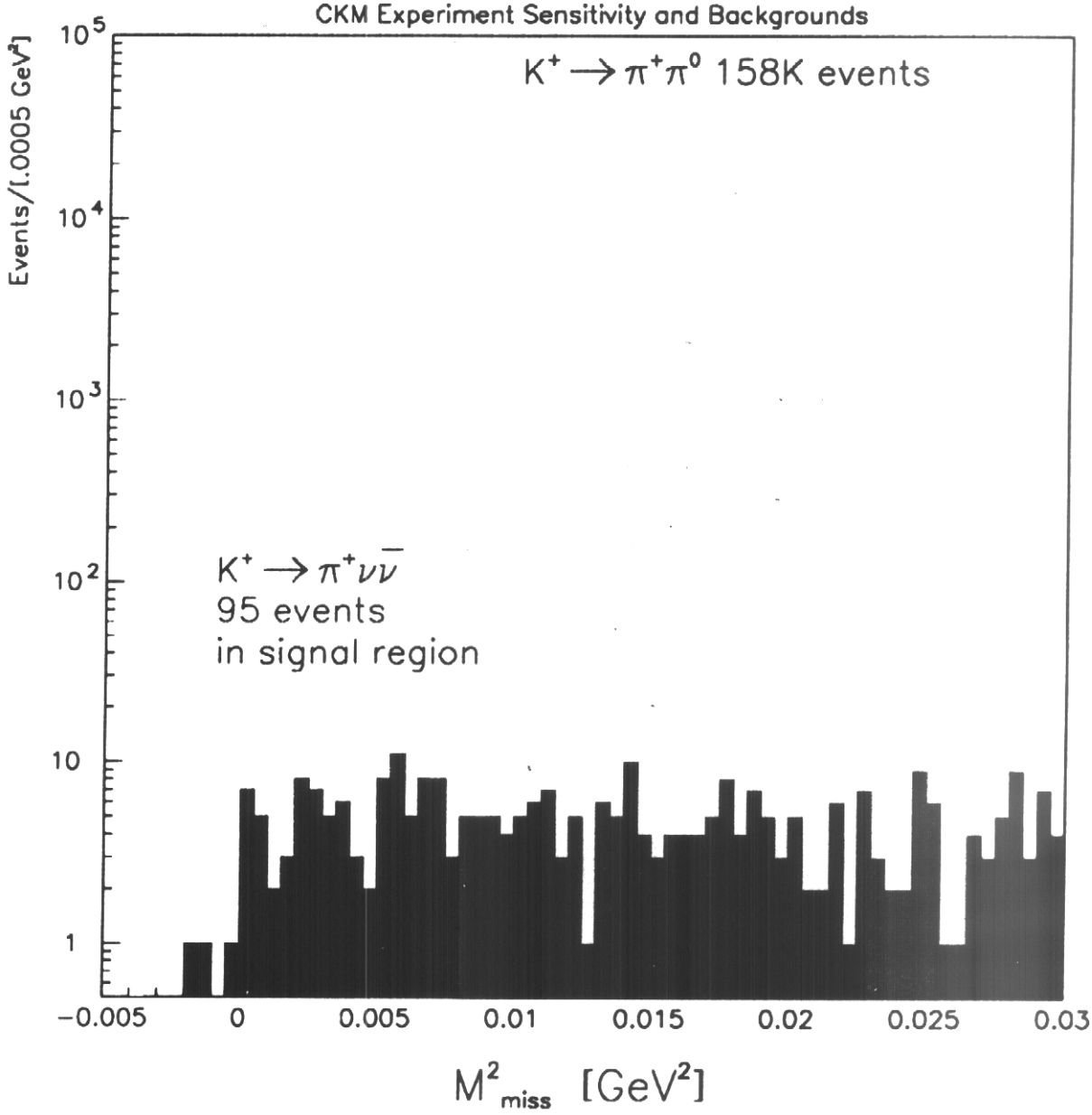
Process	Modes	Main source	Events
$K_L^0 \to \pi^0\nu\bar{\nu}$			40
K_L decays ($\bar{\gamma}$)	$\pi^0\pi^0$,$\pi^0\pi^0\pi^0$,$\pi^0\gamma\gamma$	$\pi^0\pi^0$	12.4
$K_L \to \pi^+\pi^-\pi^0$			1.7
$K_L \to \gamma\gamma$			0.02
K_L decays ($\overline{charge}$)	$\pi^\pm e^\mp\nu$,$\pi^\pm\mu^\mp\nu$,$\pi^+\pi^-$	$\pi^- e^+\nu$	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/(.0005 GeV²)
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} [GeV²]

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 $\pi^0 e^+ e^-$ 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 $K_L \to \pi^0 \nu\bar{\nu}$, $K_L \to \pi^0 e^+ e^-$, and $K_L \to \pi^0 \mu^+ \mu^-$??