KEK-IPNS

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representing the E787 collaboration

KEK Physics Seminar November 14, 2001

Latest Results on Rare Kaon Decays from the BNL E787 Experiment

Outline

- Theoretical motivation
- Experimental and data-analysis techniques
- Final results on $K^+ \to \pi^+\nu\bar{\nu}$ from E787: '98 (new) combined with '95-'97
- (Other kaon decays)
- BNL-E949 experiment

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,
G. Redlinger, R.C. Strand, and C.H. Witzig
Brookhaven National Laboratory

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

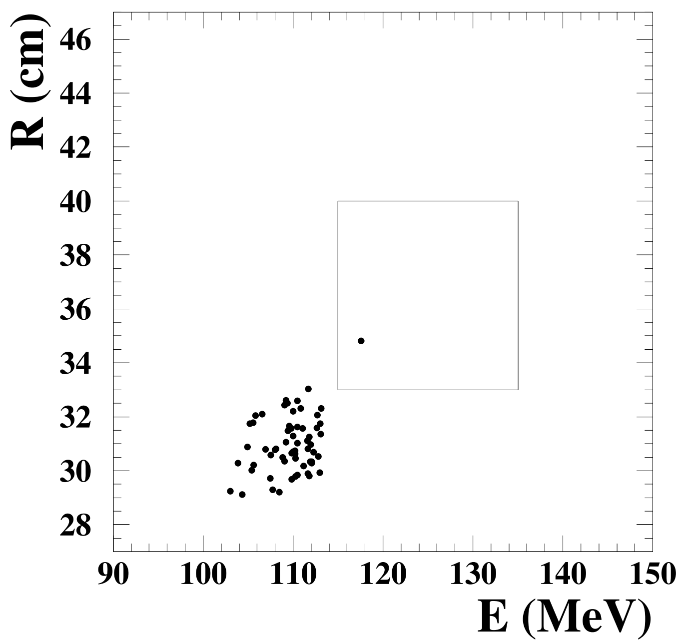
M. Ardebili, A. Bazarko, M. Convery, M.M. Ito, D.R. Marlow,
R. McPherson, P.D. Meyers, F.C. Shoemaker, A.J.S. Smith,
and J.R. Stone
Princeton University

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

History of E787 @BNL-AGS

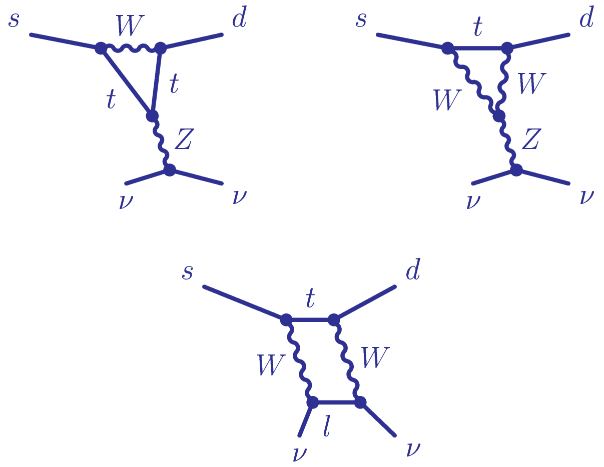
- E787 proposed in '83
  - '89-'91 [28 weeks]: $\leq 2.4 \times 10^{-9}$ (90% C.L.)
    " Search for the Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ": PRL 76(1996)
- upgraded-E787 data collection by December '98
  - '95 [18 weeks]
    " Evidence for the Decay ... ": PRL 79(1997)
  - '96 and '97 [13 + 8 weeks]
    " Further Search for the Decay ... ": PRL 84(2000)
    - branching ratio $(1.5^{+3.4}_{-1.2}) \times 10^{-10}$
    - background level [0.08±0.02 events]: 1.2×10^{-11}



  - '98 [24 weeks]
    $\Longleftarrow$ Does E787 have further evidence for the decay ??

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

$\Delta S = 1$ FCNC : induced in the SM by $W^\pm/Z^0$ loop effects as



top-quark(170GeV$/c^2$) dominant

the best place to determine $|V_{td}|$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

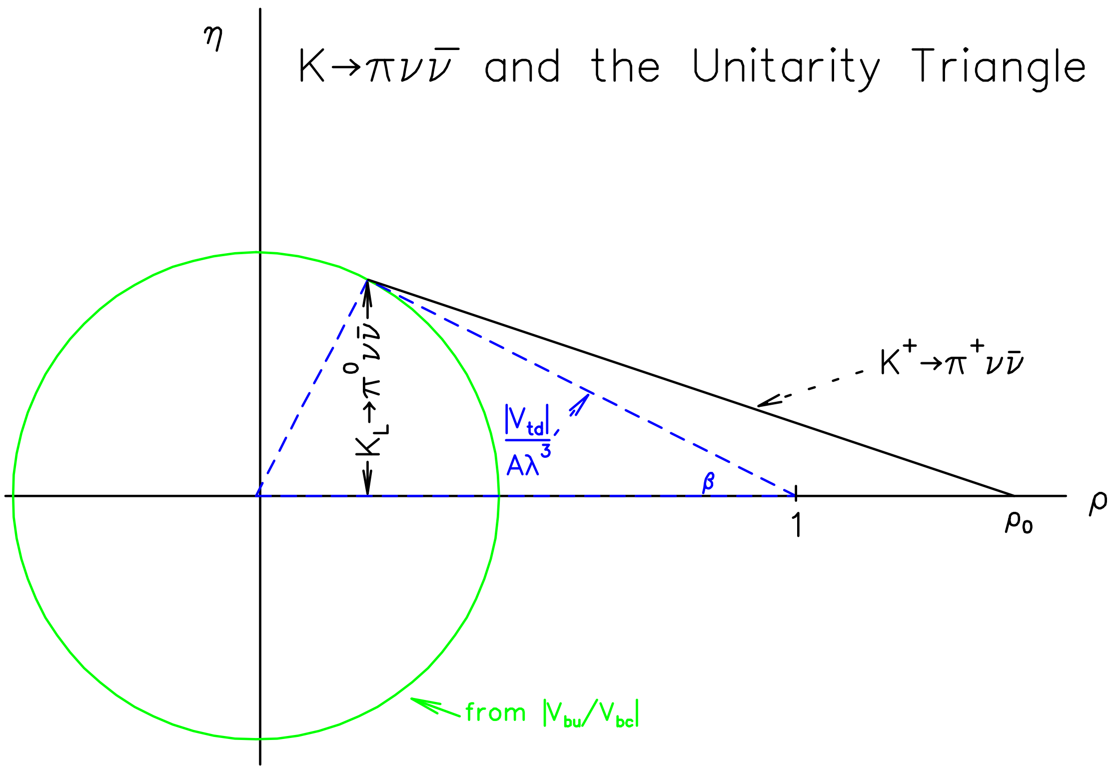
$$\lambda_t \equiv V_{ts}^* \cdot V_{td} = A^2\lambda^5 \cdot (1-\rho-i\eta)$$

rare [$A^2\lambda^5$] and precious [ρ and η]

- long-distance contributions : negligible
- $\langle K|H|\pi\rangle$ from $K^+ \to \pi^0 e^+ \nu$.
- The theoretical uncertainty $\sim 7\%$
  (m_{charm} contribution in the NLO QCD analysis)
  - a small “overlooked” term from the box diagram (1999)
  - effect of the subleading dimension-8 operators (2000)

$\underline{\text{B.R.}(K^+ \to \pi^+ \nu \bar{\nu})}$

$$4.11 \times 10^{-11} \cdot A^4 \cdot X(x_t)^2 \cdot [\ (\rho_0 - \rho)^2\ +\ \eta^2\ ]$$



(ρ, η) from ϵ_K, $|V_{ub}/V_{cb}|$, ΔM_{Bd}, ΔM_{Bs}

$\Downarrow$

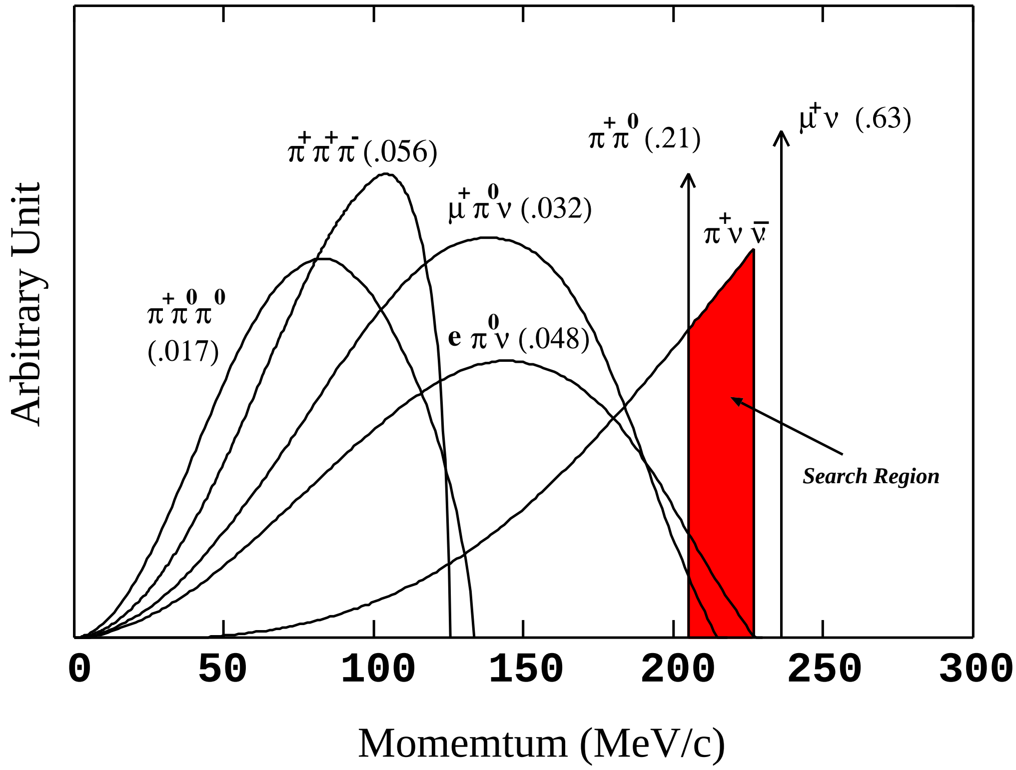
Standard Model prediction: $(0.75 \pm 0.29) \times 10^{-10}$

* $|\Delta M_{Bd}/\Delta M_{Bs}| \Rightarrow < 1.15 \times 10^{-10}$

A measurement at 1.5×10^{-10}
would be beyond the SM.

Buras: *hep-ph/0101336*
Isidori: *hep-ph/0110255*
Buchalla: *hep-ph/0110313*

stopped K$^+$ decay to π^+ plus "nothing"



the π^+ ($< 227\mathrm{MeV}/c$) from 3-body decay

Background rejection is essential in this experiment.

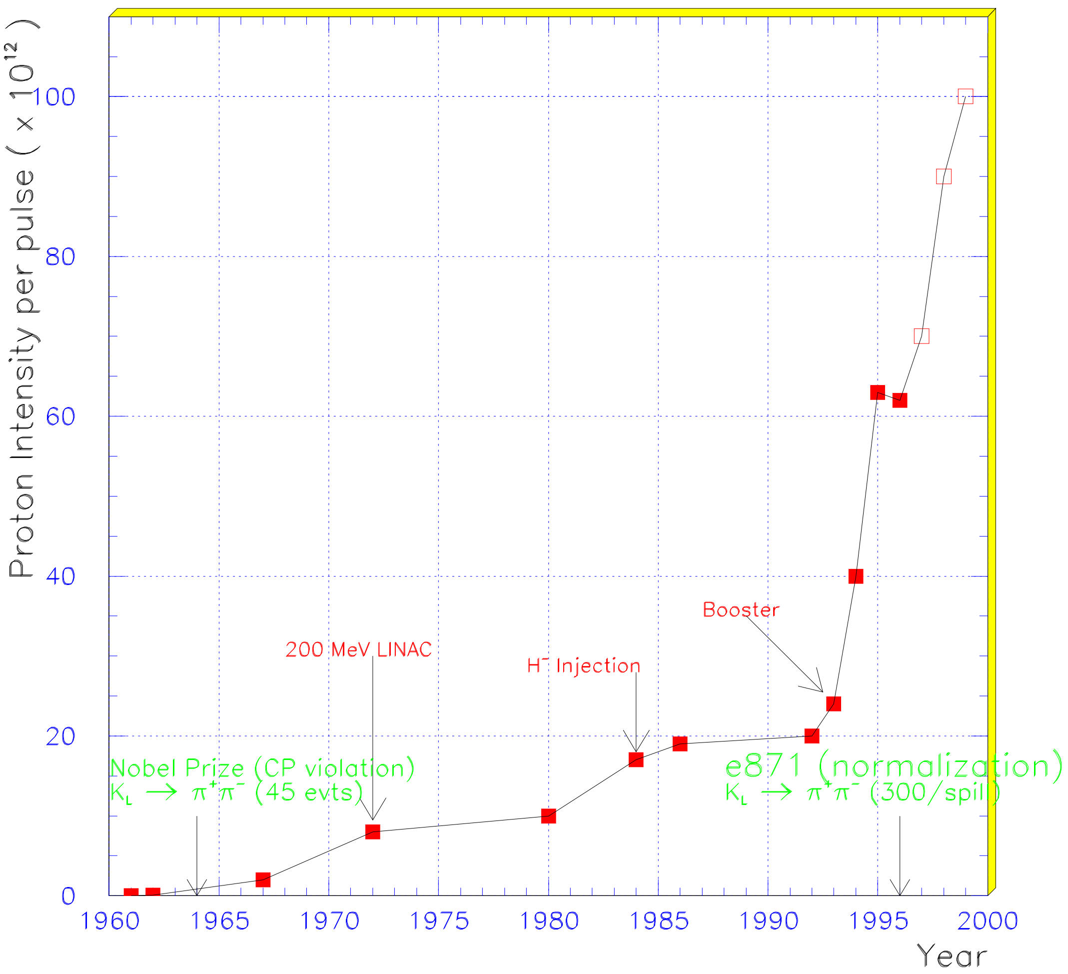
- Kinematics : Momentum/Energy/Range
- μ^+ rejection $\Longleftrightarrow$ $\mathrm{K}^+ \to \mu^+\nu$
- Extra particles (γ) Veto $\Longleftrightarrow$ $\mathrm{K}^+ \to \pi^+\pi^0$

each weapon should have rejection of $10^5 \sim 10^6$
$\leftarrow$ reliable estimation using real data

BNL-AGS : 24GeV Protons

Tp $\equiv$ 10E12(Tera) protons/spill

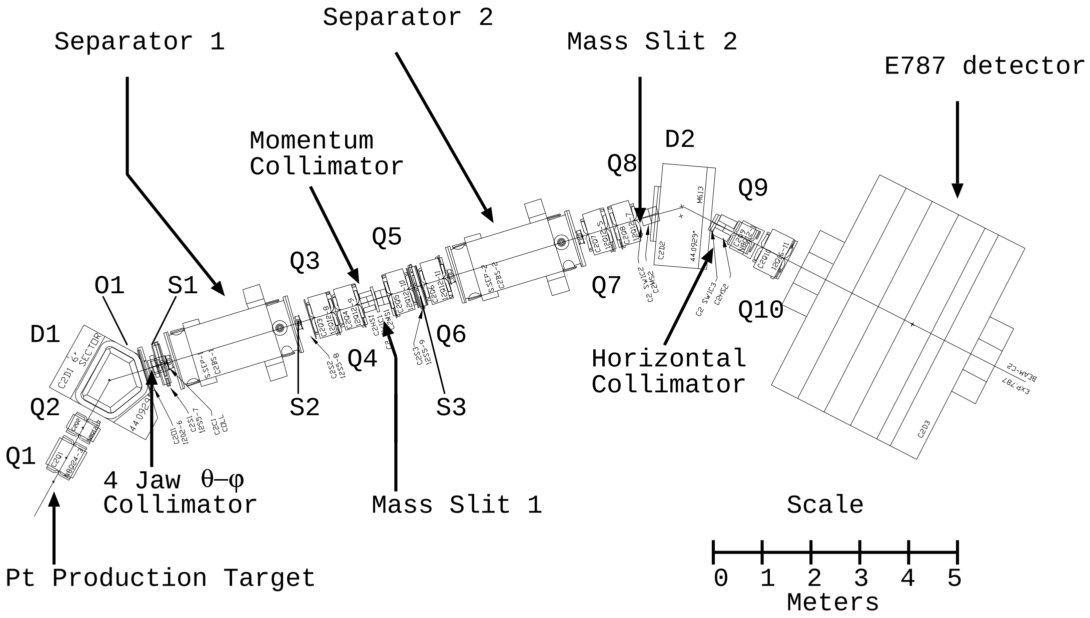
AGS History



Improvement \ year	'95	'96	'97	'98
beam spill (sec)	1.2/1.6	1.6		2.2
duty factor (%)	38/44	44		52 ($\times$1.37)

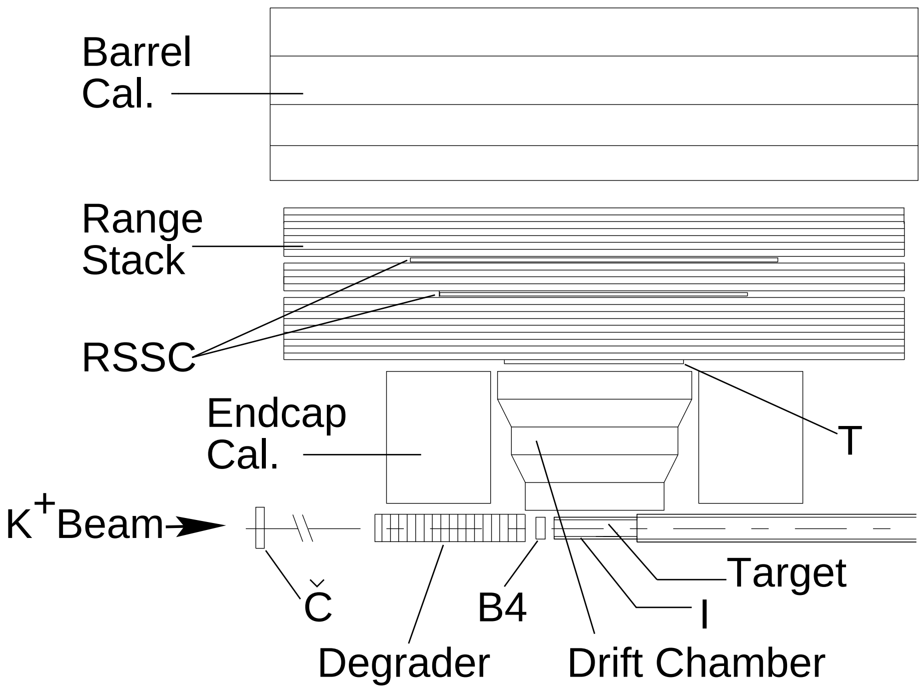
LESB3: a two-stage separated 800-MeV/c kaon beamline

J. Doornbos et al., NIM A 444, 546 (2000)



- $\sim 5 \times 10^5$ $K^+/10^{12}$ protons on target
- K/π ratio > 3

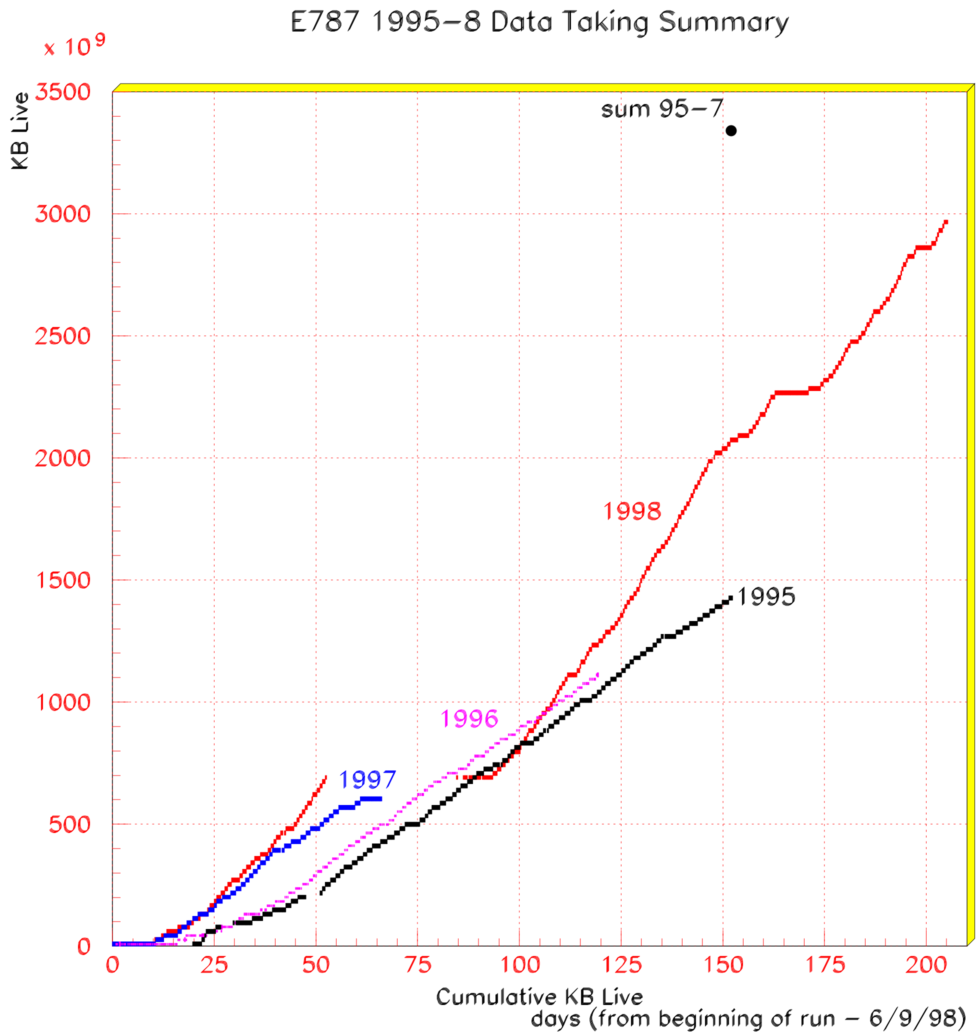
- stopped K^+
  (slowed by BeO degrader and coming to rest)
  $\sim$ 20% @ 790MeV/c



the beam momentum $\searrow$ (less degrader)

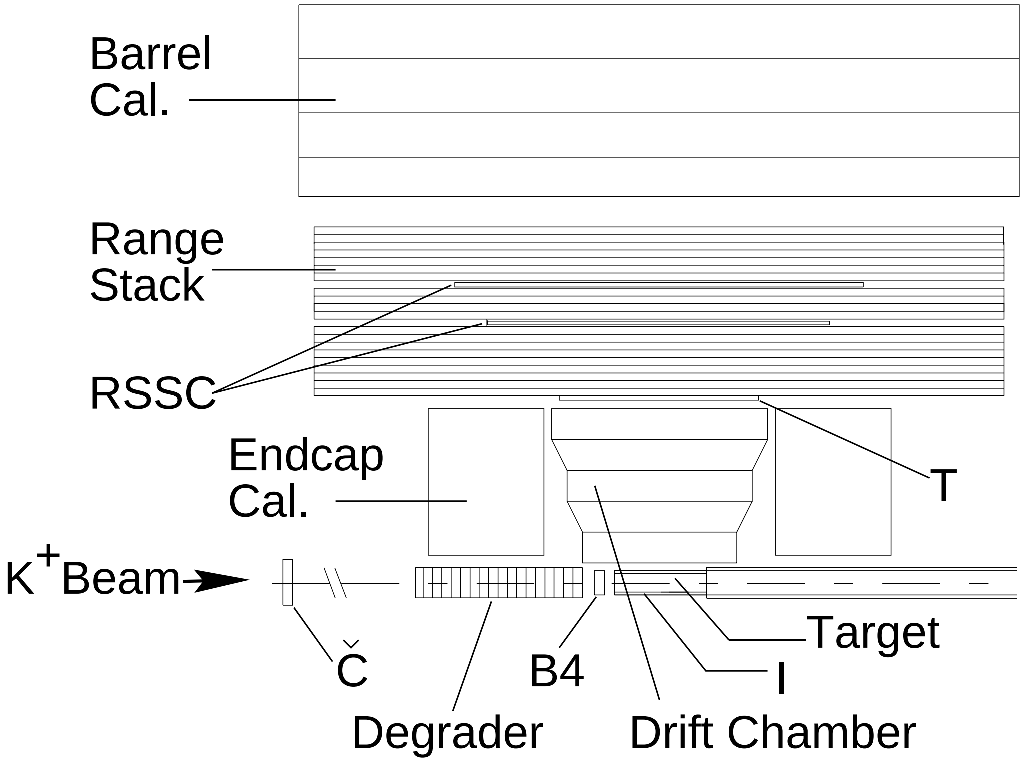
$\Longrightarrow$ K^+ stopping fraction $\nearrow$

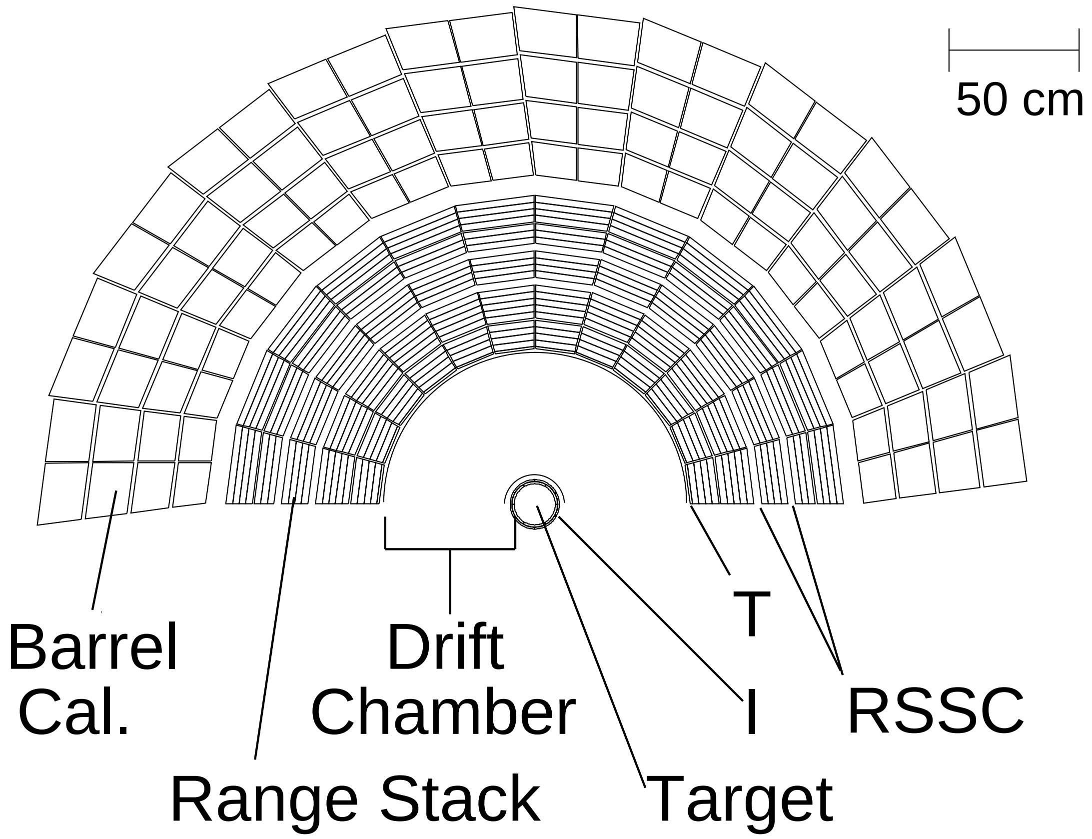
Improvement \ year	'95	'96	'97	'98
kaon momentum (MeV/c)	790	730	710	
stopping fraction (%)	20	25	28 (×1.5)	

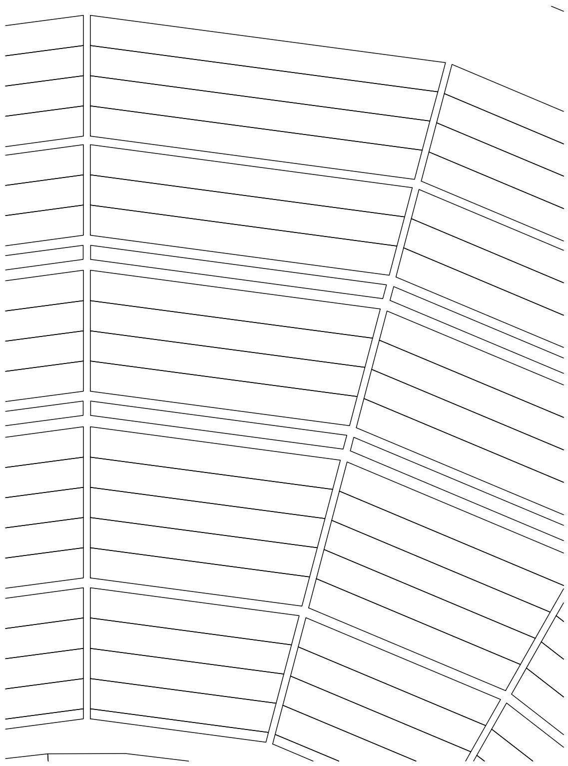


- Number of kaons incident on the target (N_K):

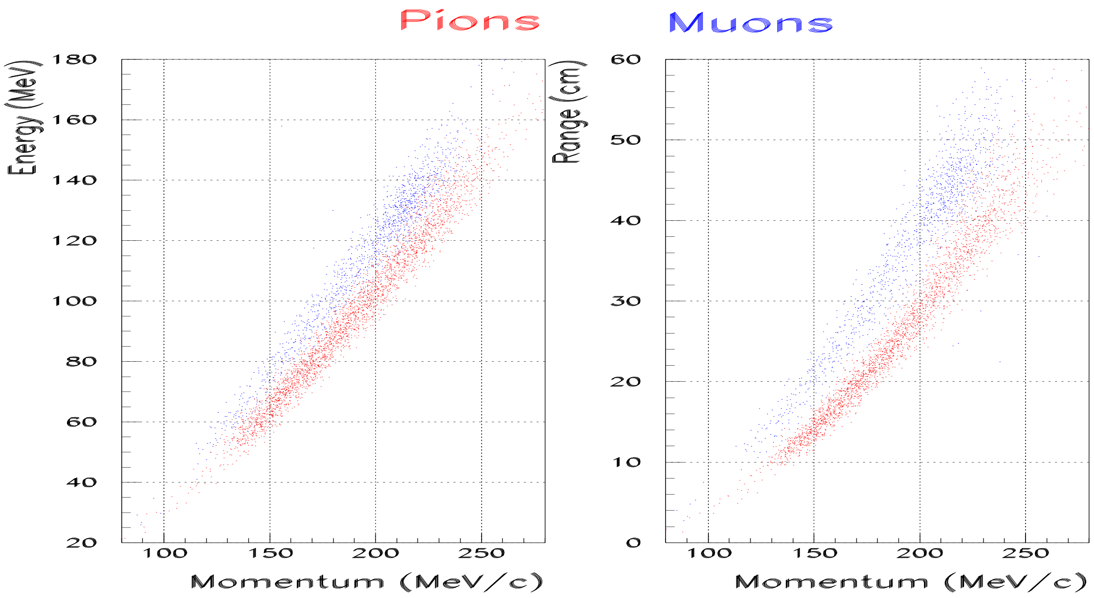
	1995-97	1998
N_K	3.2×10^{12}	2.7×10^{12}


Barrel
Cal.
Range
Stack
RSSC
Endcap
Cal.
T
K^+Beam
Target
Č
B4
I
Degrader
Drift Chamber

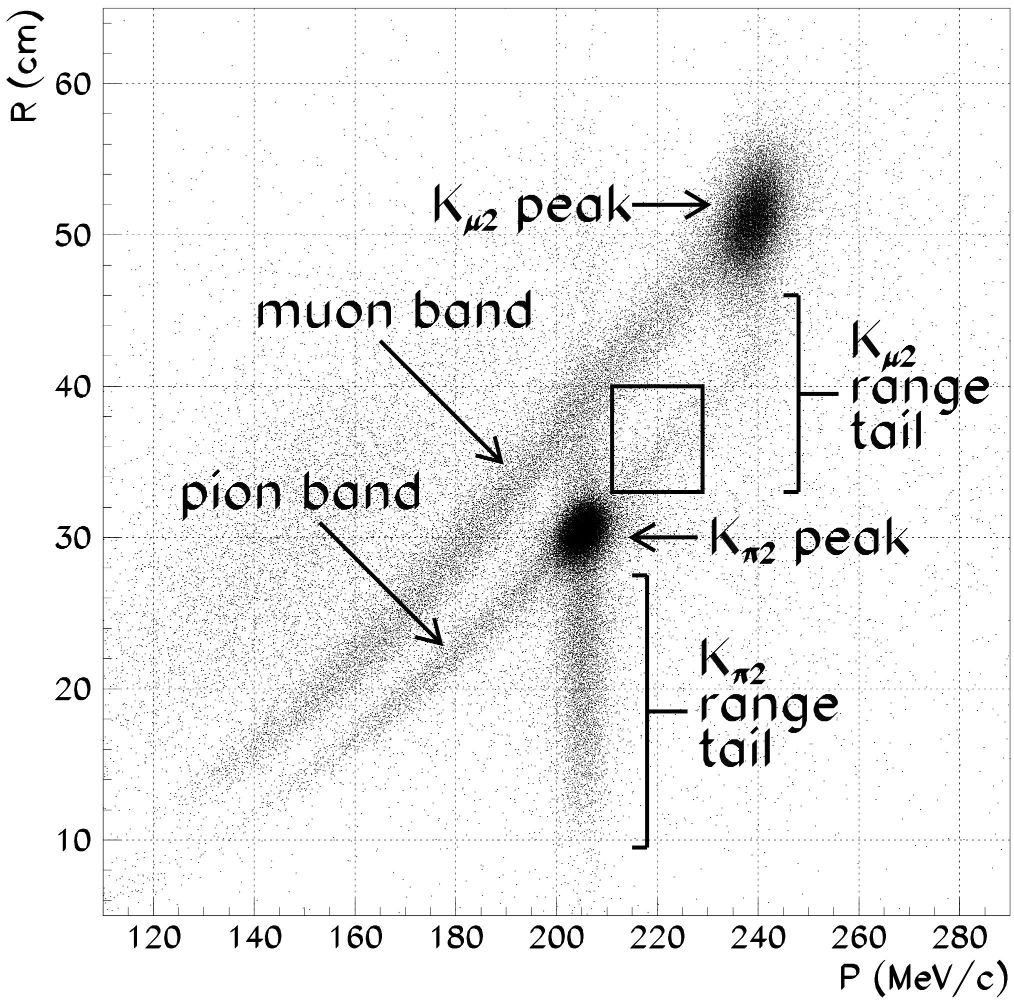

50 cm
T
Barrel
Cal.
Drift
Chamber
I
RSSC
Range Stack
Target

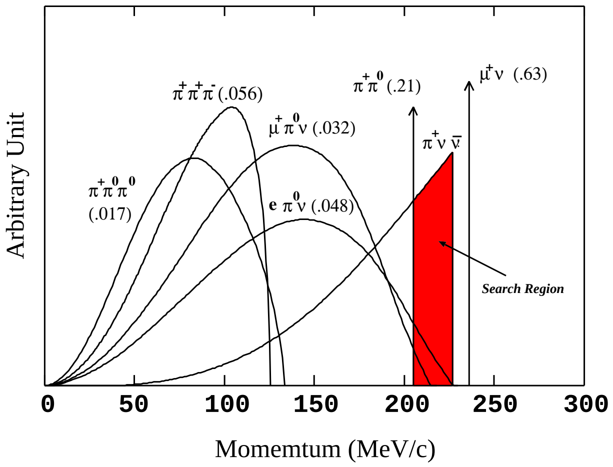


- Energy/Range - Momentum relation

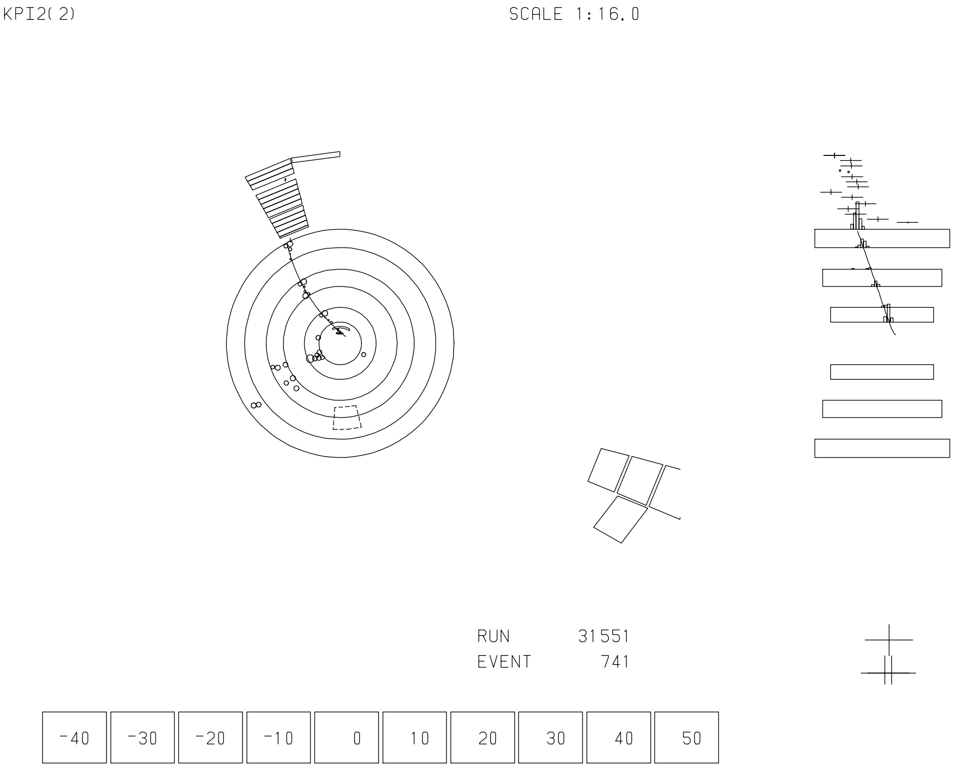


Charged tracks in the E787 spectrometer





$K^+ \to \pi^+\pi^0(\to \gamma\gamma)$ Background Rejection: **online/offline photon detection**

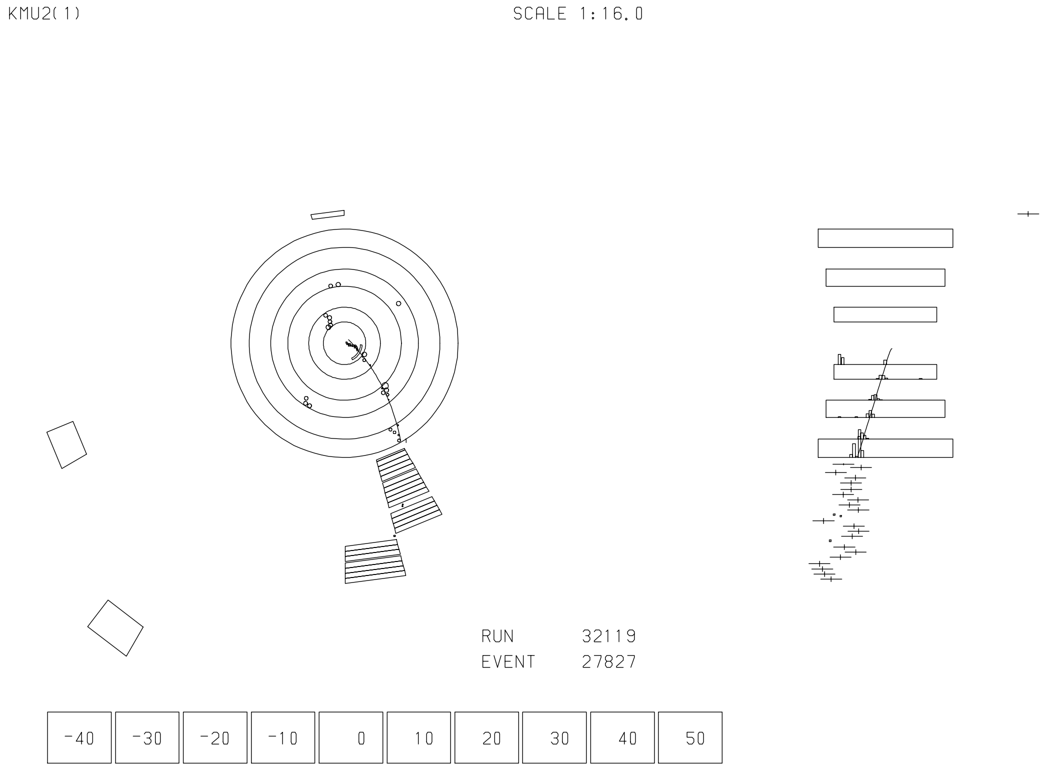


extra activity: hits within $\pm$ a few nsec, $\geq \sim 1$ MeV

Photon detection vs. Calorimetry

Photon detection	Calorimetry
(no clustering)	clustering
	Energy
	Position
Timing	
Inefficiency	
$\leftrightarrow$ pile-up in high rates	

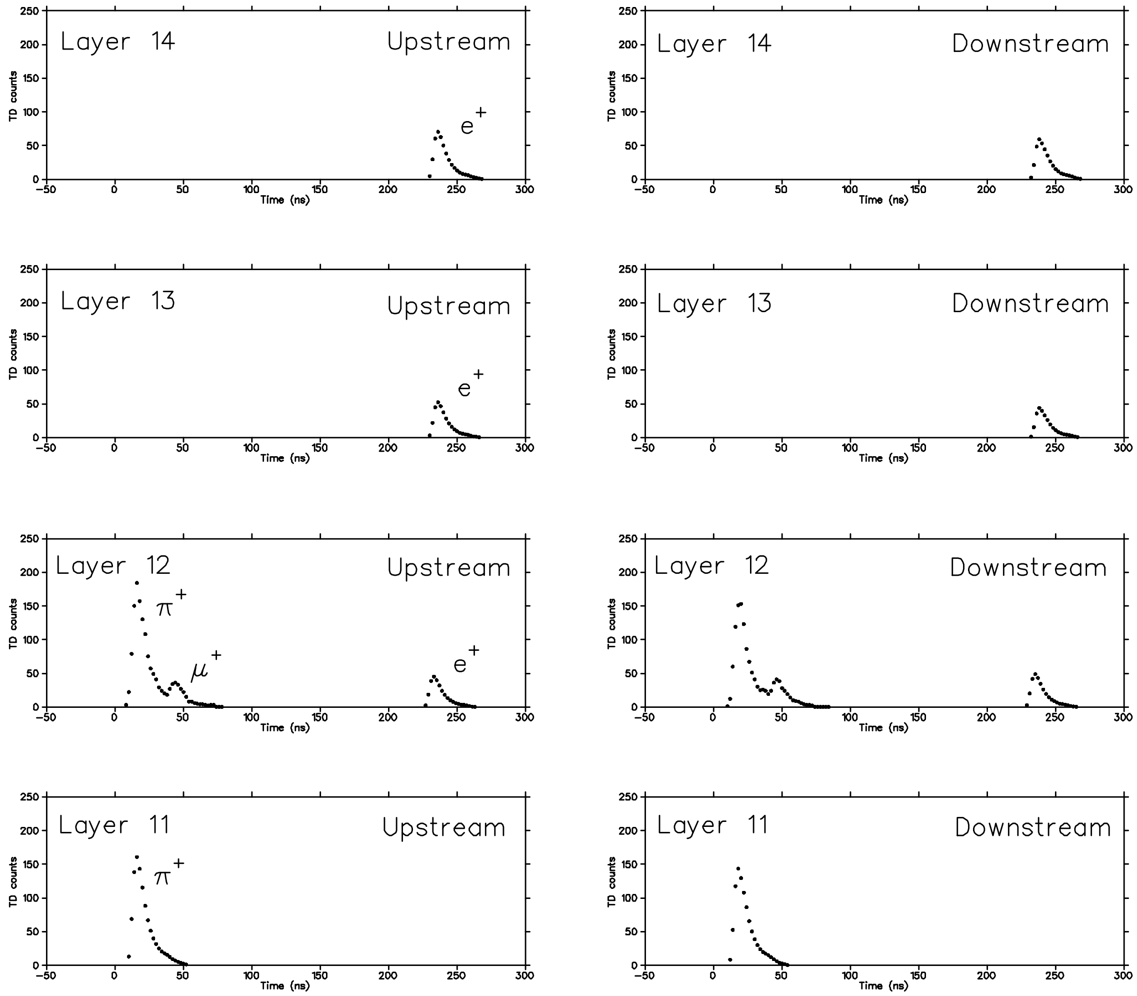
Acceptance $\Longleftarrow$ loss due to accidental hits:
monitoring with the $K^+ \to \mu^+\nu$ sample



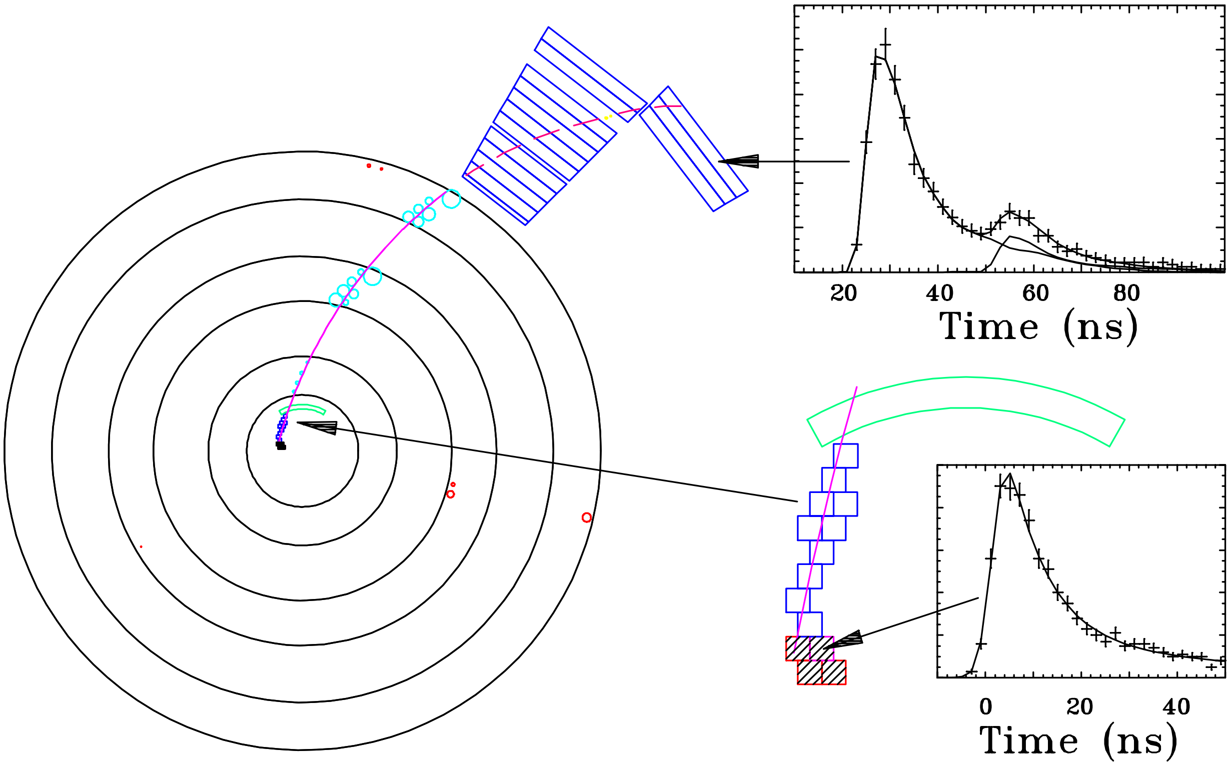
extra activity accompanying the muon from $K_{\mu 2}$

control Rejection vs. Acceptance with real data vs. muons from Range-tail and from Muon-band

- $\pi^+ \to \mu^+ \to e^+$ decay chain
  recorded by 500-MHz wavweform digitizers [TD]



- online: Level-1 trigger using TD control board with ASIC's
  - π^+ tagging efficiency $\sim$ 60%
  - μ^+ rejection factor $\sim$ 15-25
- offline: double-pulse fitting algorithm
  and criteria on μ^+ and e^+ signals

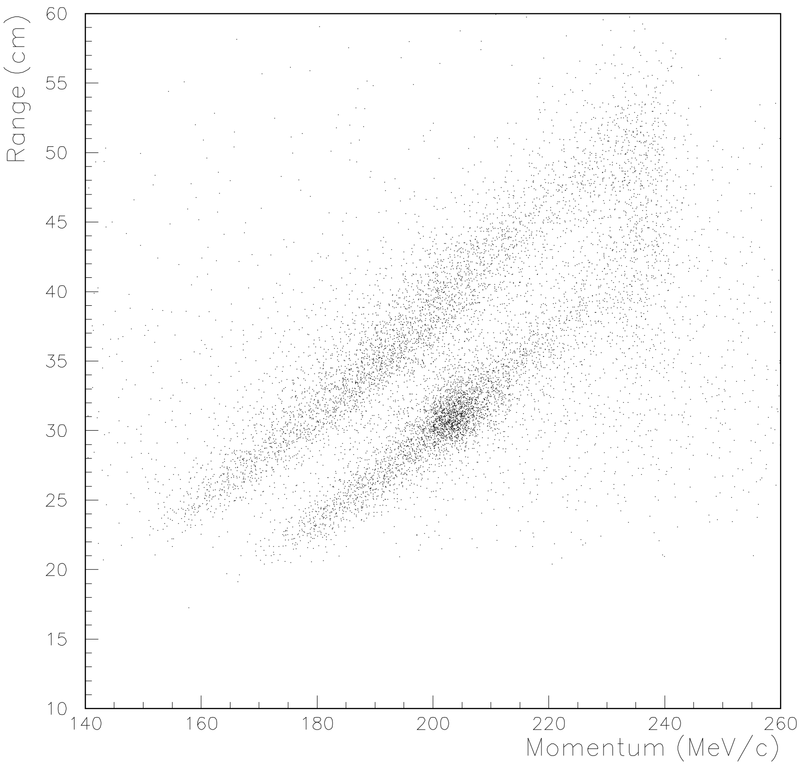


Evidence for the Decay $K^+ \to \pi^+\nu\bar{\nu}$

S. Adler *et al.*(E787 collaboration), PRL79(1997)2204

'95 data [18 weeks]

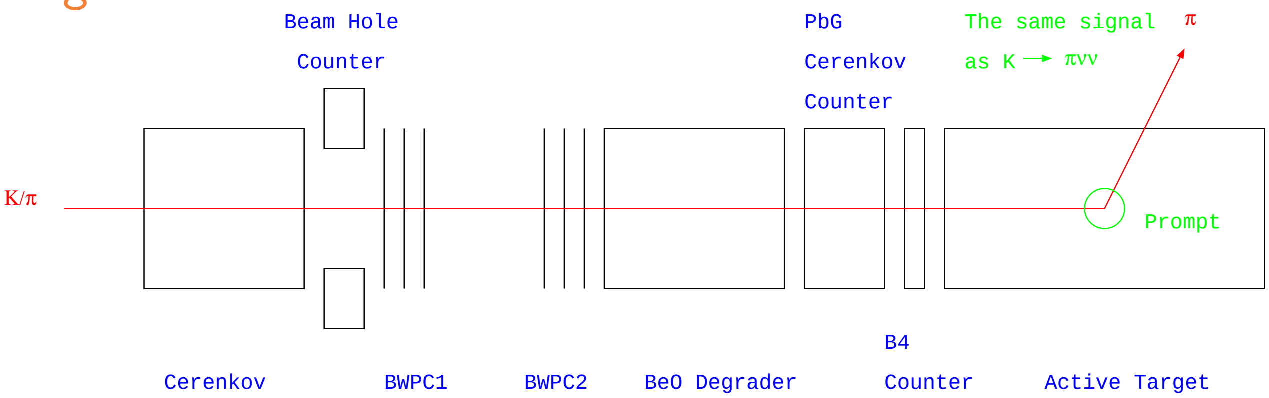
$\pi^+\nu\bar{\nu}$ data, 1st-pass reconstruction



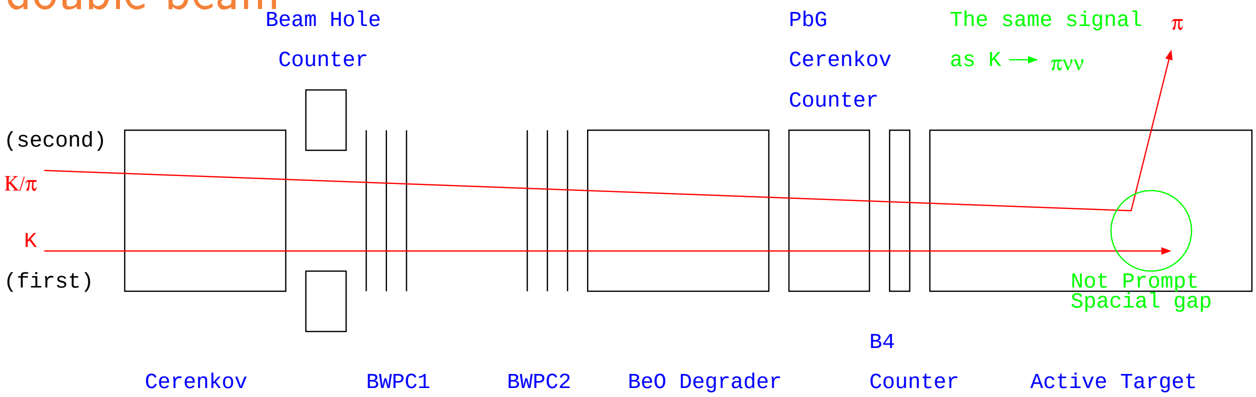
background sources:

- $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$) peak
- $K^+ \to \mu^+\nu$ ($K_{\mu 2}$) range tail
- muon band
- pion band:
  - "π^+ scattering":
    π^+ in the beam or K^+ decay in flight
  - Charge-Exchange interation:
    $K^+ n \to K^0 p$ in the target ("CEX")

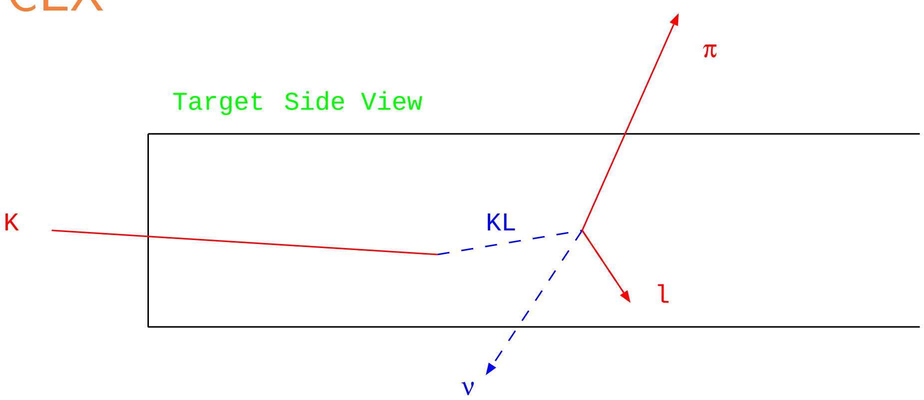
single-beam



double-beam

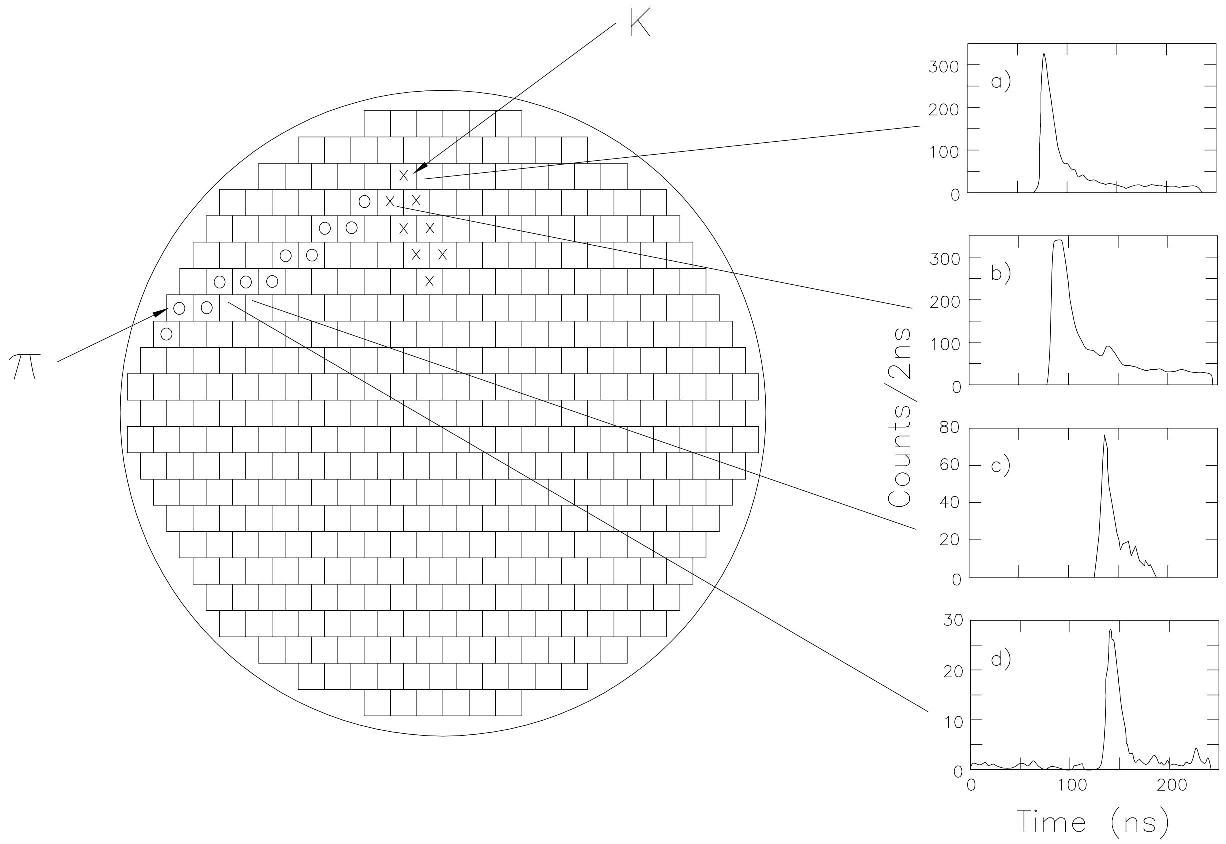


CEX



$K^+ \to \pi^+$ decay in the target

- 5mm $\times$ 5mm scintillating fibers
- 500-MHz GaAs CCD digitizers



Signal region ("BOX") in multi-dimensional "cut" space

1. π^+ kinematic region cuts:
   - Momentum: $211 < \mathrm{P} < 229$ MeV/c ("above $K_{\pi 2}$")
   - Range (R), Kinetic Energy (E)
   - Range-Momentum relation (muon band)
2. "Rejection" cuts:
   - Photon Detection ($K_{\pi 2}$)
   - $\pi^+ \to \mu^+ \to e^+$ decay chain (muon)
   - Beam cuts

These cuts characterize the "likelihood" of signal events.

"function" cuts: control Rej.·Acc. continuously

Background studies

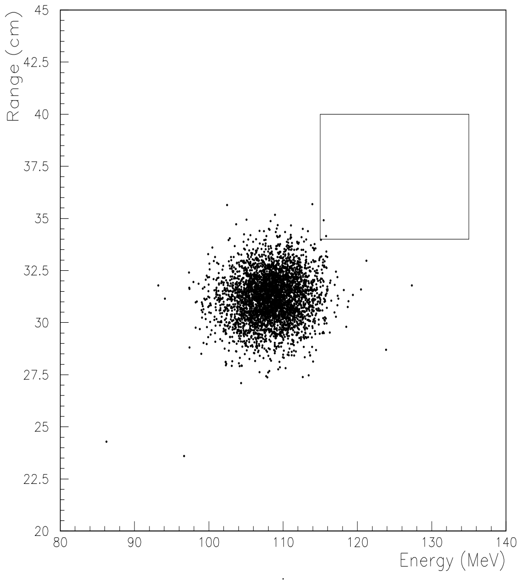
- **invert** at least one of the cuts to
  - enhance the background collected by the trigger
  - prevent candidate events from being examined ("Blind Analysis")
- Cuts were **frozen** at this stage (This is a "counting" experiment).
- Estimated levels of backgrounds in the signal region

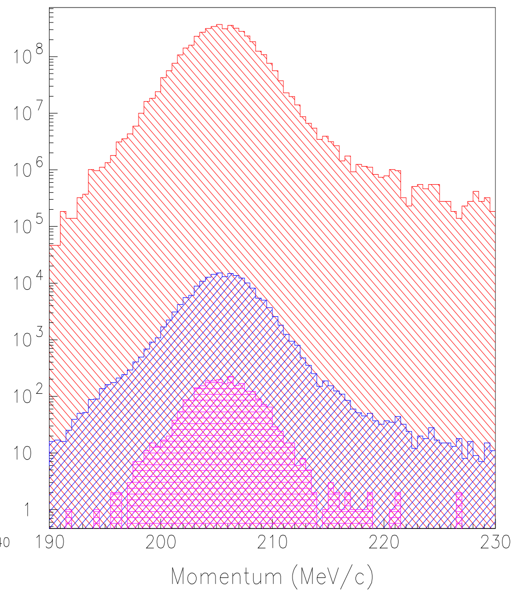
Source	No. of events	
	1995-97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam (single+double)	0.02 ± 0.02	0.004 ± 0.001
K^+ charge exchange	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total background	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$) background study

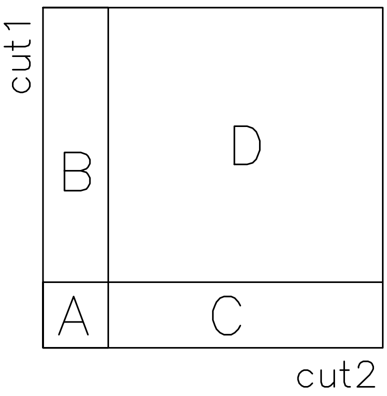
- Kinematics : Energy/Range/Momentum peak
- γ detection ($\pi^0 \to \gamma\gamma$)

[γ detected] [π^+ in $K_{\pi 2}$ R/E peak]





π^+ kinematic tail γ detection inefficiency

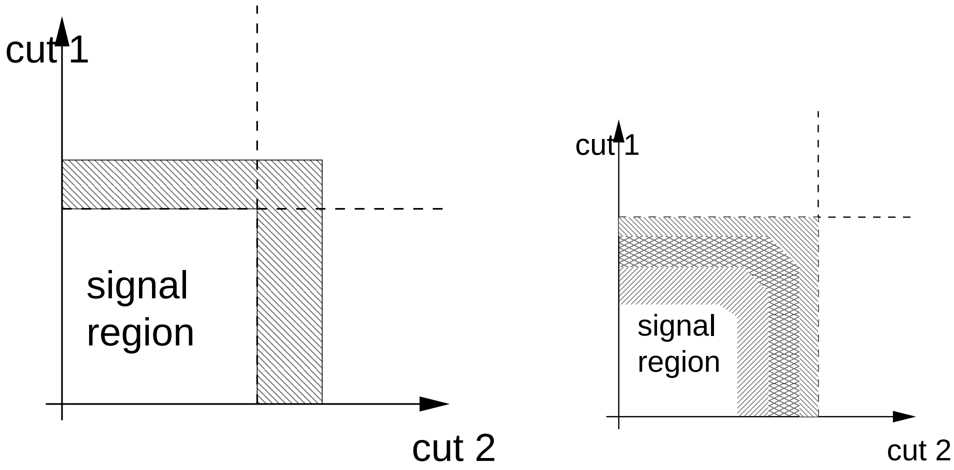


Acceptance

Acceptance factors	method	1995-97	1998
K^+ stop efficiency	BR($K_{\mu2}$)	0.704	0.702
K^+ decay after 2 ns	$K_{\mu2}$	0.850	0.851
$K^+ \to \pi^+\nu\bar{\nu}$ phase space	M.C.	0.155	0.136
Solid angle acceptance	M.C.	0.407	0.409
π^+ stop efficiency	M.C.	0.513	0.527
Reconstruction efficiency	$K_{\mu2}$	0.959	0.969
Other kinematic constraints	π_{scat},$K_{\pi2}$	0.665	0.554
$\pi - \mu -$ e decay acceptance	π_{scat}	0.306	0.392
Beam and target analysis	$K_{\mu2}$	0.699	0.706
Accidental loss	$K_{\mu2}$	0.785	0.751
Total acceptance		0.21%	0.196%

	1995-97	1998
N_K	3.2×10^{12}	2.7×10^{12}
Acceptance ($\times 10^{-2}$)	0.21 $\pm 0.01_{stat} \pm 0.02_{syst}$	0.196 $\pm 0.005_{stat} \pm 0.010_{syst}$
Sensitivity	1.50×10^{-10}	1.89×10^{-10}
Background (events)	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

signal-to-background function
"just-outside" and "inside" the BOX region



1. sub-divide the "cut" space into 7.5K bins
   - signal region: i=1,486
   - just-outside the signal region: i=487,7500
2. for each bin, evaluate
   - Background b_i
   - Acceptance A_i

   - Exercise:
     $\Sigma_{i=1}^{486} b_i = 0.066$ and $\Sigma_{i=1}^{486} A_i = 0.00196$
     (as in the previous slide)
   - $\Sigma_{i=487}^{7500} b_i = 0.9 \pm 0.7$ and $\Sigma_{i=487}^{7500} A_i = 0.00098$
     (background $\times 13$, acceptance $\times 0.5$)
3. make a table of (b_i, A_i, f_i) , where
   $f_i = (BR \times A_i \times N_K)/b_i$, the signal-to-background funtion
   and BR is an assumption for normalization.
4. Count the number of events d_i in each bin

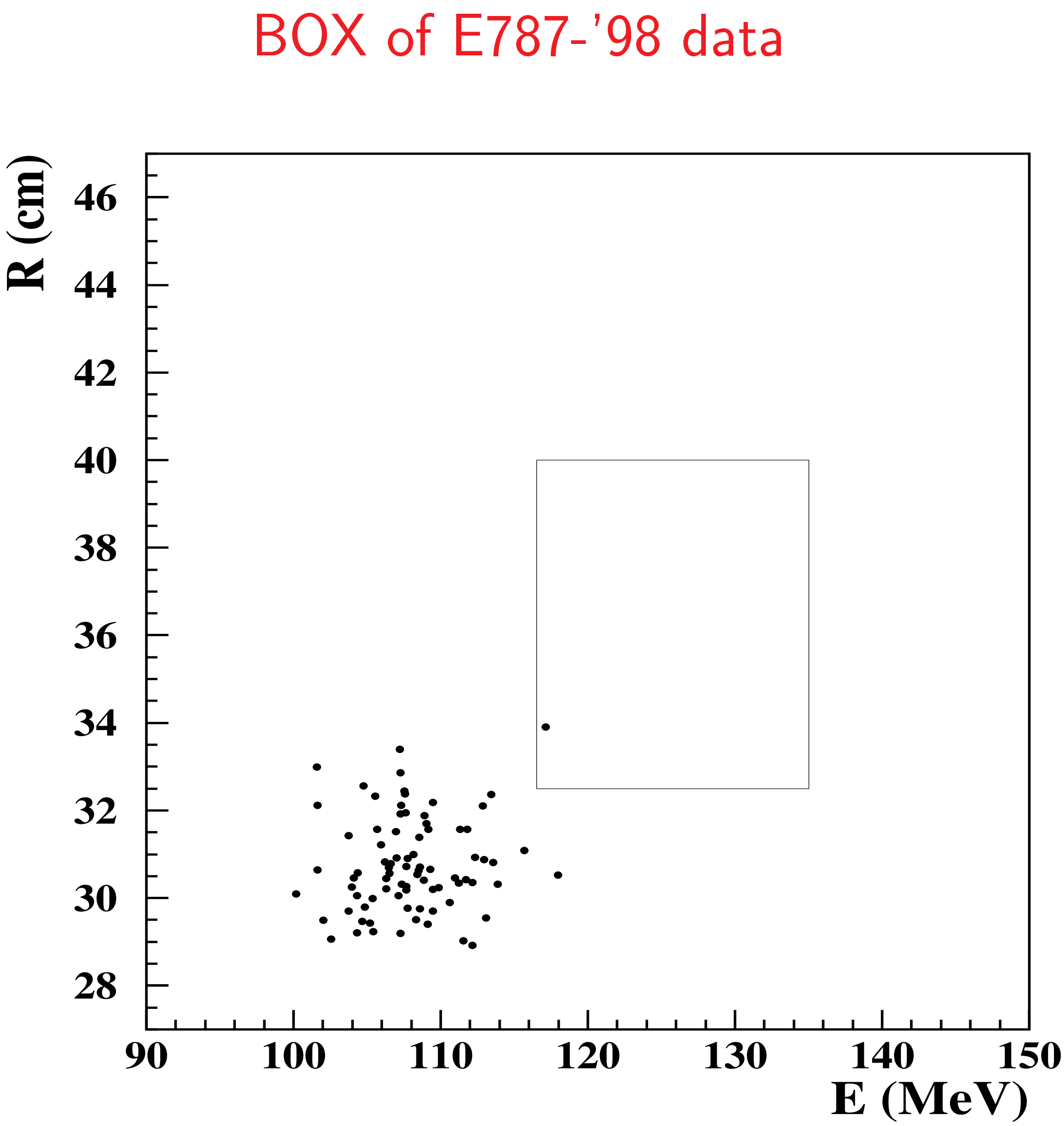
just-outside the BOX region

(i=487,7500 : background=0.9 $\pm$ 0.7 events)

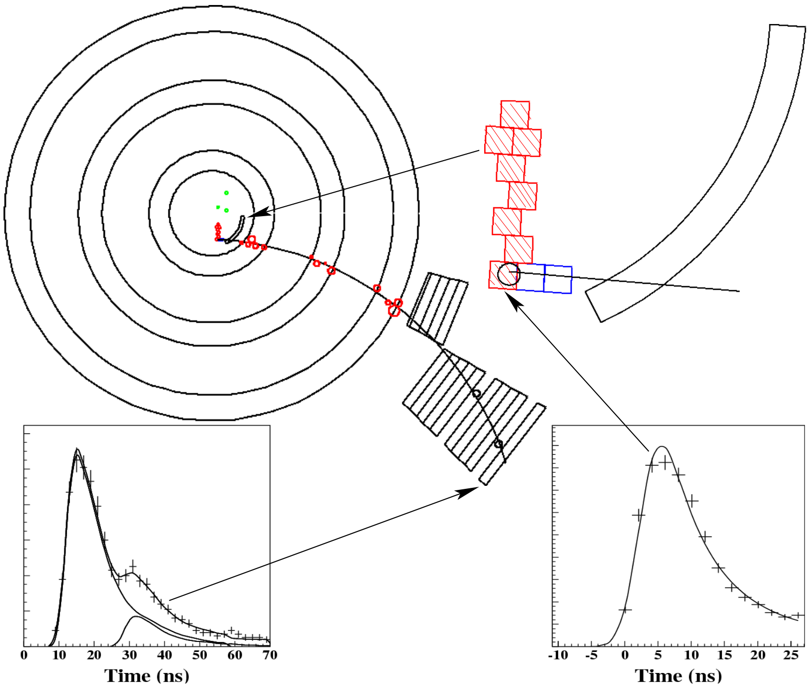
<u>Two events were observed.</u>

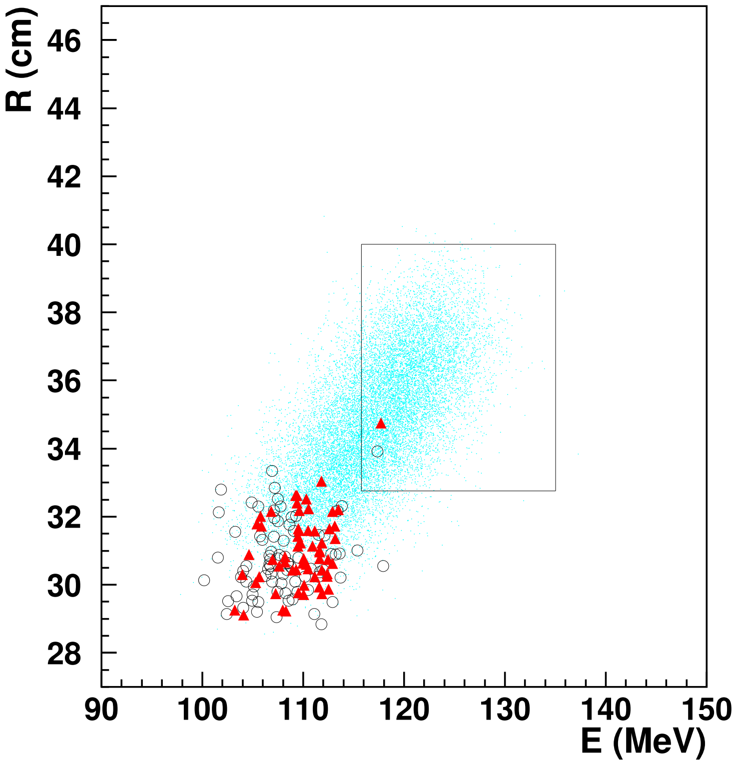
quantities	Event B1	Event B2
P/R/E	×	○
R-P relation	○	○
Photon	×	○
$\pi^+ \to \mu^+ \to e^+$ chain	○	×
Beam	○	○
f_i	0.07	0.7

- In agreement with the expected background events in this region. HOWEVER,
- We got intersted in Event-B2, because it was located deep in the kinematic BOX cuts (P=224.8MeV/c, R=37.1cm, E=125.6MeV). It only failed the $\pi^+ \to \mu^+ \to e^+$ cut by the waveform digitizer.
- Why did the event fail ? $\pi^+ \to \mu^+$ decay at rest appeared at an early time (11 nsec), and was suspected as "fluctuation of pulse shape".
- Since the cuts were frozen, we decided <u>we do not consider Event-B2 as a signal,</u> (though it could be "a signal contamination" to the outside-the-BOX region).


BOX of E787-'98 data
R (cm)
46
44
42
40
38
36
34
32
30
28
90
100
110
120
130
140
150
E (MeV)

Further Evidence for the Decay $K^+ \to \pi^+ \nu \bar{\nu}$





Two signal events were observed.

quantities		Event A '95	Event C '98
P	(MeV/c)	218.2	214.0
R	(cm)	34.7	33.9
E	(MeV)	117.7	117.4
Photon		○	○
$K^+ \rightarrow \pi^+$ decay time	(ns)	23.9	4.2
$\pi^+ \rightarrow \mu^+$ decay time	(ns)	26.9	16.5
$\mu^+ \rightarrow e^+$ decay time	(ns)	3253	5333
Beam		○	○
f_i		35	3.6

	1995-97	1998
N_K	3.2×10^{12}	2.7×10^{12}
Acceptance ($\times 10^{-2}$)	0.21 $\pm 0.01_{stat} \pm 0.02_{syst}$	0.196 $\pm 0.005_{stat} \pm 0.010_{syst}$
Sensitivity	1.50×10^{-10}	1.89×10^{-10}
Observation (events)	1	1
Background (events)	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

Statistics

T. Junk (Carleton, OPAL), NIM **A434**, 435 (1999)
"Confidence Level Computation for Combining Searches with Small Statistics"

example: LEP Higgs Working Group's searches for Higgs Bosons Decaying into Two Photons, *hep-ex/0107035*

- assumption:
  the expected signal and background levels are small
  (use of Poisson statistics), and
  only a few events are observed.
- 486 bins for the 1998 signal region:
  (b_i, A_i, f_i) plus d_i , i=1,486
  can be regarded as
  "486 statistically-independent searches"
  and be combined.
- 1995-97 result (interpreted as 2-bin measurements) can also be combined.
- provid the computer program
  with a set of (b_i, f_i, d_i) based on an BR assumption,
  and the program calulcates the C.L. of the BR from
  Modified Frequentist's approach
- loop over possible BR's,
  and get limits on BR with the C.L. you want.

Results on $K^+ \to \pi^+ \nu\bar{\nu}$ from E787

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \;=\; 1.57^{+1.75}_{-0.83} \times 10^{-10}$$

(68% C.L. interval)

- with unitarity, $\bar{m}_t(m_t) = 166 \pm 5$ GeV$/c^2$, $V_{cb} = 0.041 \pm 0.002$ and without V_{cb}, ϵ_K,

$$0.007 \;<\; |V_{td}| < \; 0.030$$

- $\lambda_t \;\equiv\; V^*_{ts} \cdot V_{td} \;=\; A^2\lambda^5 \cdot (1 - \rho - i\eta)$

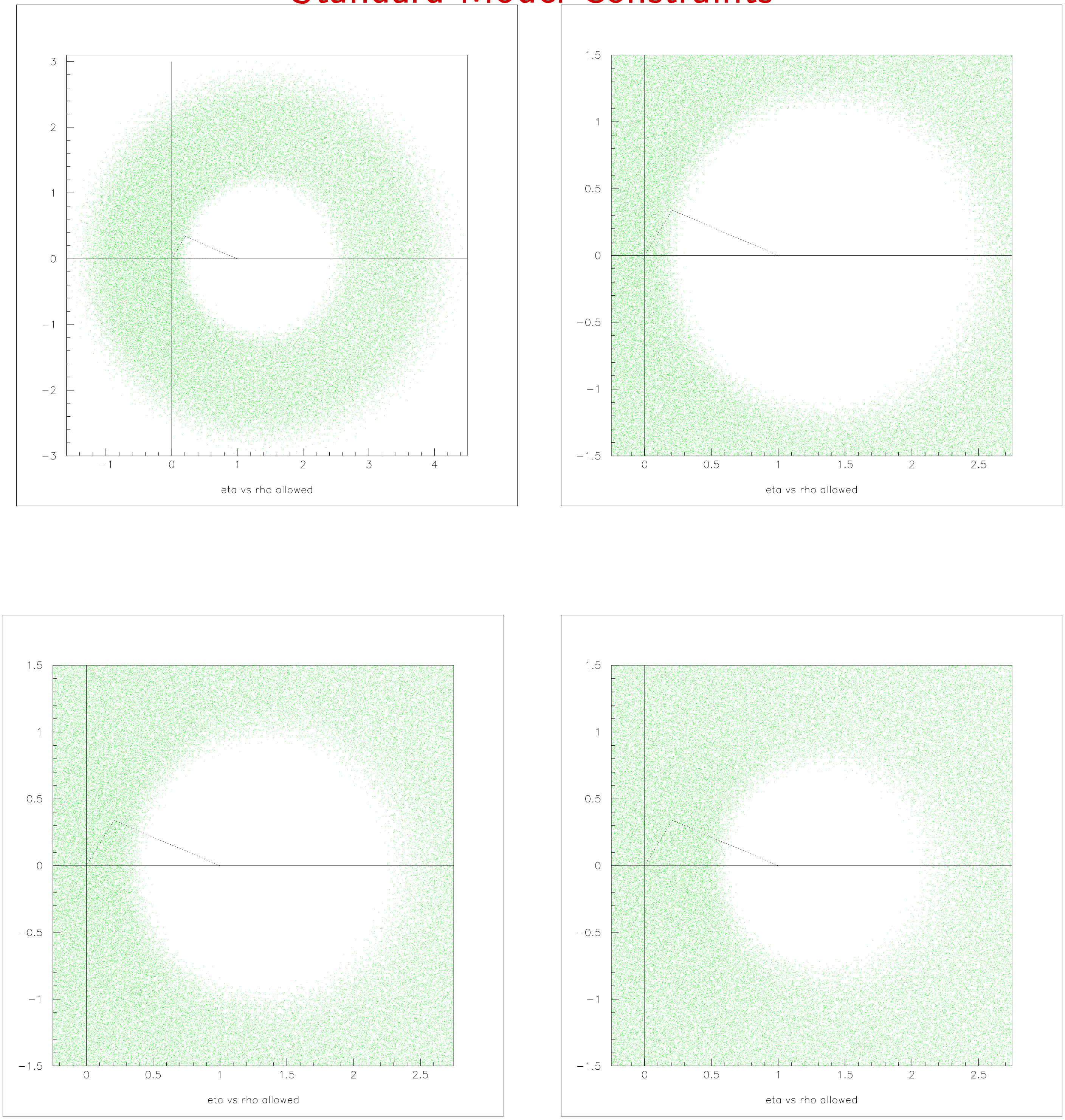
$$2.9 \times 10^{-4} \;<\; |\lambda_t| \;<\; 1.2 \times 10^{-3}$$

$$-0.88 \times 10^{-3} \;<\; \mathrm{Re}(\lambda_t) \;<\; 1.2 \times 10^{-3}$$

$$\mathrm{Im}(\lambda_t) \;<\; 1.0 \times 10^{-3}$$

without reference to the B system, ϵ_K, ϵ'/ϵ.

Standard Model Constraints



E949

An experiment to measure the branching ratio B($K^+ \to \pi^+ \nu \overline{\nu}$)

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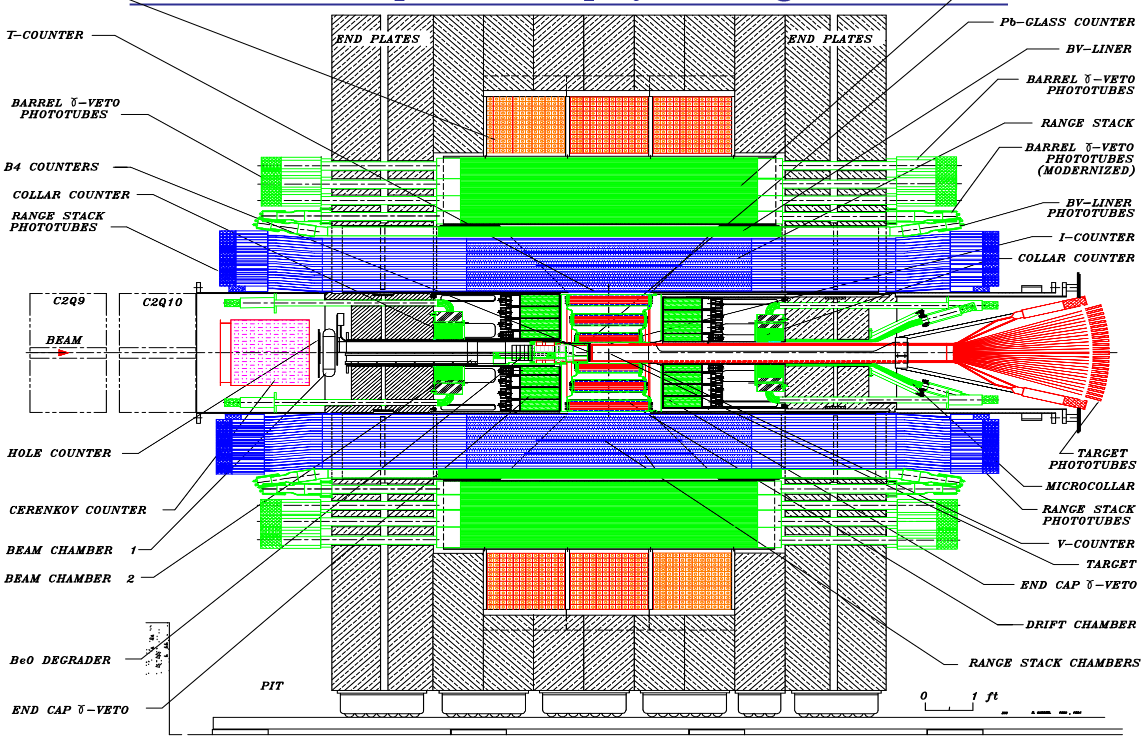
TRIUMF

E949 http://www.phy.bnl.gov/e949/

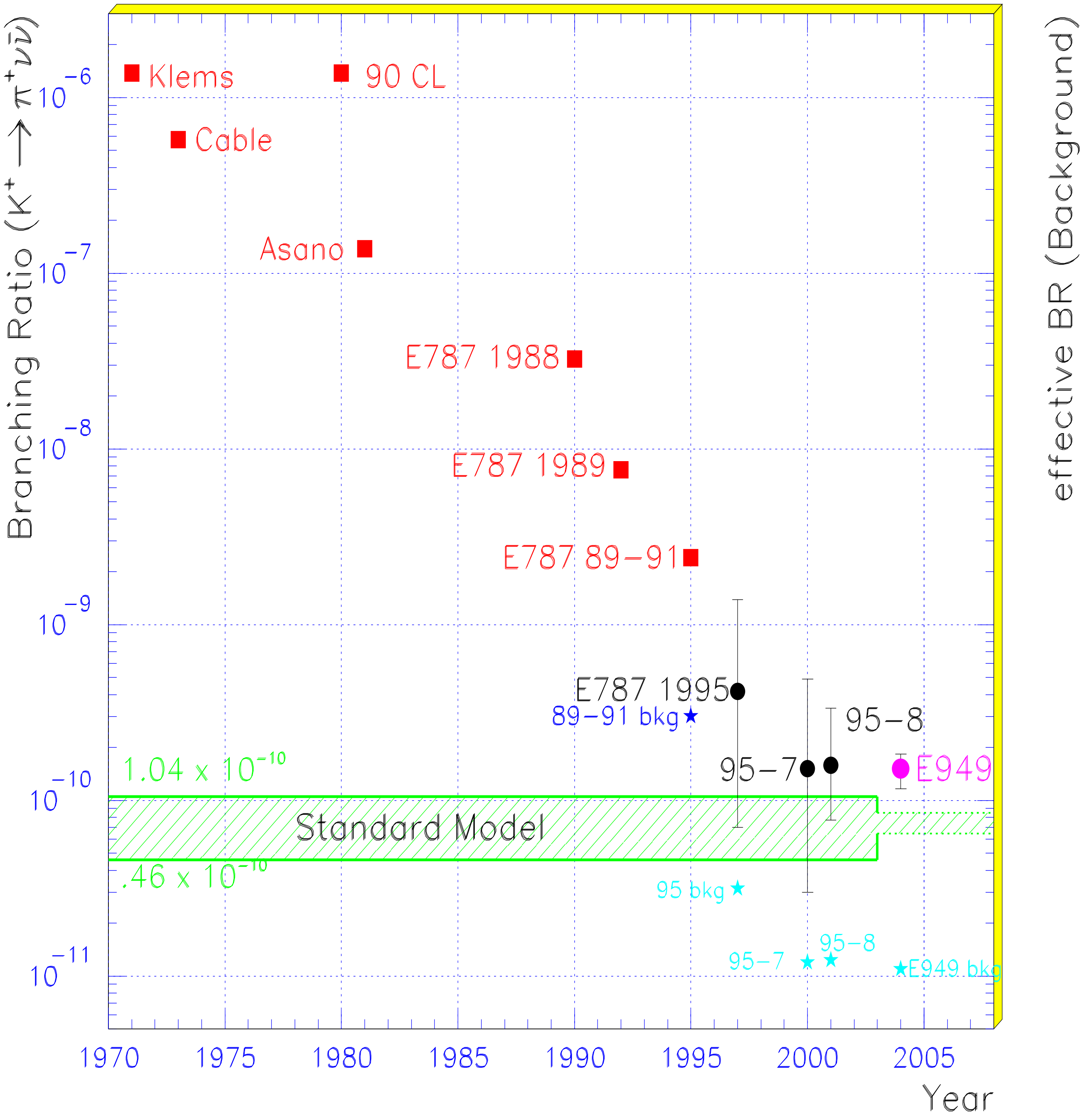


Detector upgrade from E787

1. Barrel Liner shower counter
2. new/improved Photon Veto counters around the beamline
3. new B4 counter, degrader
4. Trigger: programable Level0 board, Mean Timers
5. RS TDC readout (tag $\mu^+ \to e^+$ without TD):
   $\Longrightarrow$ deadtime reduction
6. RS Monitor system using LEDs
7. ...

- Optimization of running mode and analysis
- Sensitivity (8–14)$\times 10^{-12}$ in 6000 hr
  ($\sim$ 2 years of running with RHIC;
  engineering run Sep-Nov '01, physics run from '02).
- Determine $|V_{ts}^* \cdot V_{td}|$ to 20–30%.

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



Summary:

- E787 reached the sensitivity for $K^+ \to \pi^+\nu\bar{\nu}$ predicted by the SM ($\sim 0.8 \times 10^{-10}$)
- Final Results on $K^+ \to \pi^+\nu\bar{\nu}$ from E787:
  - 2 events consistent with the signature for $K^+ \to \pi^+\nu\bar{\nu}$ have been observed.
  - $BR(K^+ \to \pi^+\nu\bar{\nu}) = 1.57^{+1.75}_{-0.83} \times 10^{-10}$
  - $0.007 < |V_{td}| < 0.030$
    assuming unitarity, $\bar{m}_t(m_t)$, V_{cb}
  - Limits on $\lambda_t \equiv V^*_{ts} \cdot V_{td}$
    without reference to B, ϵ_K, ϵ'/ϵ:

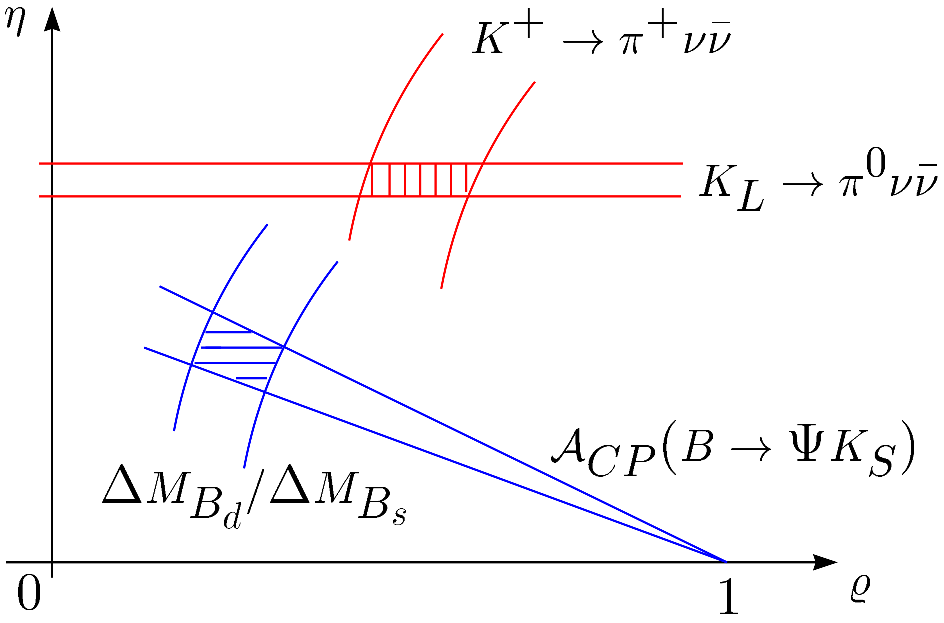
$$2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-3}$$

$$-0.88 \times 10^{-3} < \mathrm{Re}(\lambda_t) < 1.2 \times 10^{-3}$$

$$\mathrm{Im}(\lambda_t) < 1.0 \times 10^{-3}$$

- PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ "below $K_{\pi 2}$"
  (KEKTC5 in the next week)

Summary (cont.):



- The BNL E949 Experiment is getting to be an important particle-physics experiment in the next 3-5 years; is BR($K^+ \to \pi^+ \nu\bar{\nu}$) really consistent with the SM ?
  - Engineering run (Sep-Nov '01) was successfully completed.
  - Aimed at $\leq$ 10^{-11} or $5 \sim 10$ SM events.
  - $10 \sim 20$ events due to beyond_the_SM ??
- and the future ...
  (50GeV-PS Workshop @KEK in December)