T. K. Komatsubara

KEK-IPNS

Kaon Decay Workshop @KEK February'01

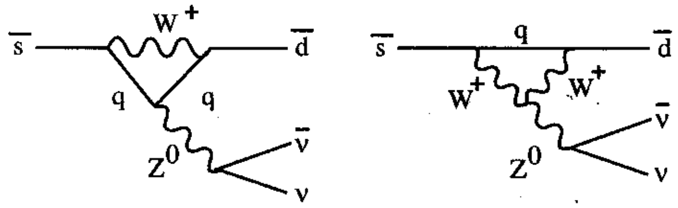
From E787 to E949 and the future: stopped-kaon experiment for $\underline{K^+ \to \pi^+ \nu\bar{\nu}}$

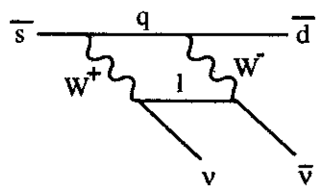
Outline :

- Introduction
- BNL-E787 experiment: detector
- Why the $\underline{K^+ \to \pi^+ \nu\bar{\nu}}$ experiment is so "difficult" ?
  (from my personal viewpoint)
- BNL-E949 experiment [2001~]
- The future

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

no FCNC at tree level : induced by loop effects as





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

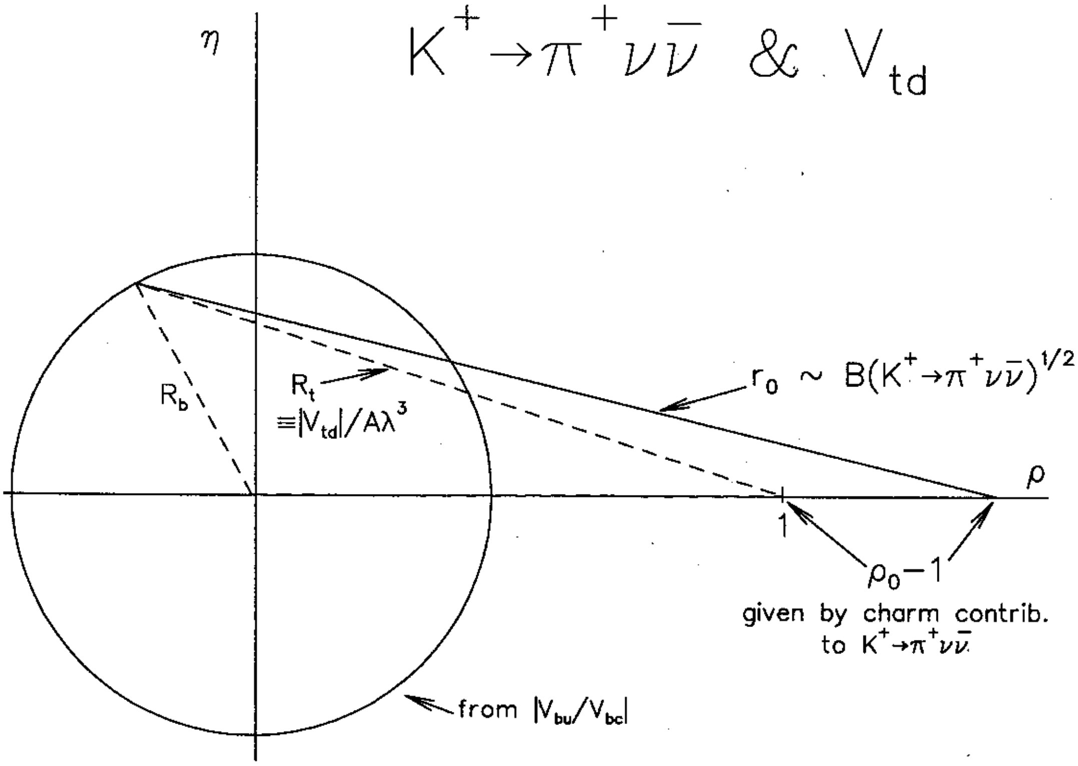
the best place to determine $|V_{td}|$

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

- 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)

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

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



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

$\Downarrow$

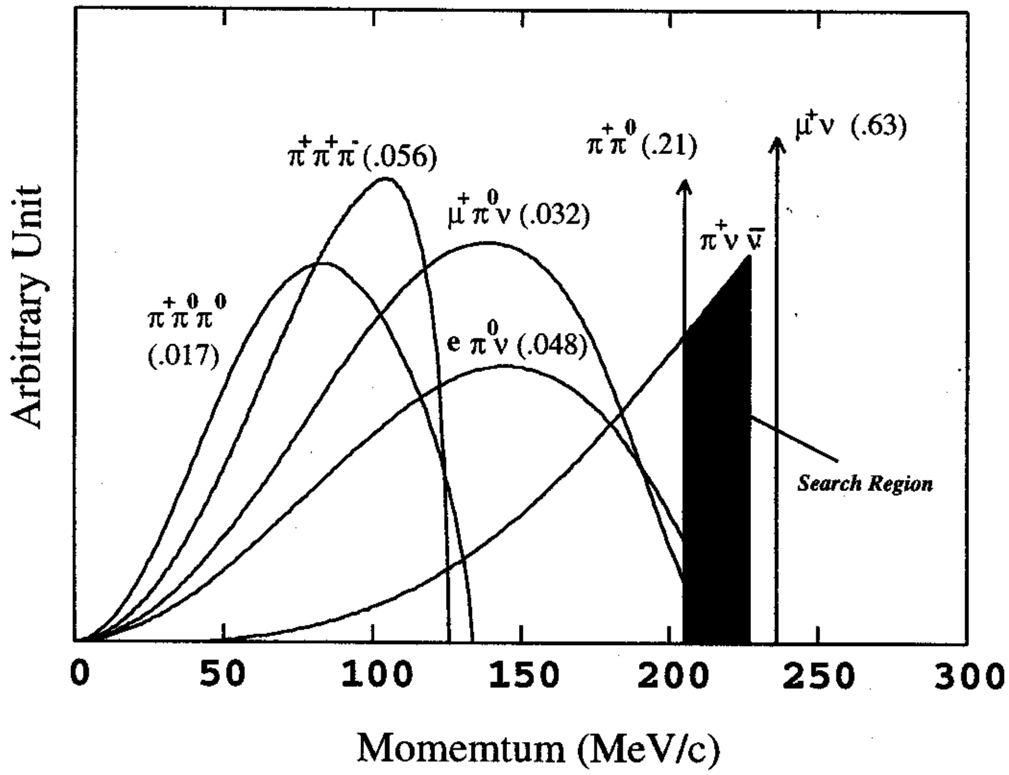
a Standard Model prediction: $(0.75 \pm 0.29) \times 10^{-10}$

a recent review by Buras: *hep-ph/0101336*

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

a measurement at 1.5×10^{-10} would be beyond_the_SM

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



<u>the π^+ ($<$ 227MeV/c) from 3-body decay</u>

Background rejection is essential in this experiment.

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

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

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 [BNL-Princeton-TRIUMF] proposed in '83
  - LESB1 beamline ($K/\pi \sim 0.5$)
  - '89-'91 [28 weeks]: $\leq 2.4 \times 10^{-9}$ (90% C.L.)

- upgraded-E787
  [BNL-KEK-Osaka-Princeton-TRIUMF-Alberta + Fukui, Kyoto]
  - LESB3 beamline ($K/\pi > 3$, $\times 5$ K^+/spill)
  - major upgrade of detector/trigger/DAQ

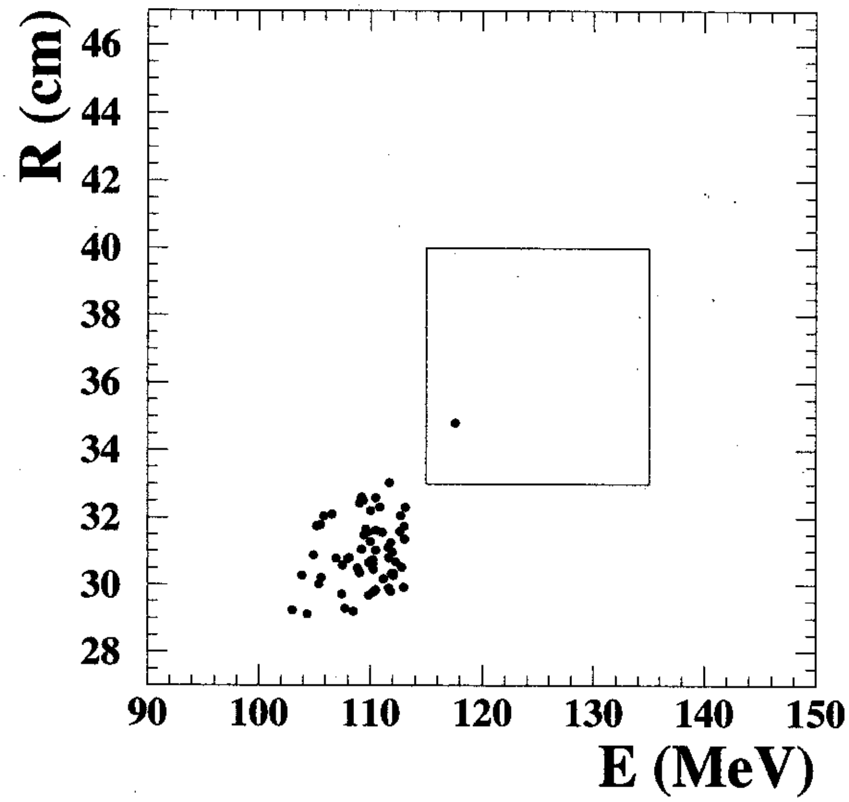
  '95 (first physics run): 18 weeks,

  '96 and '97: 13 + 8 weeks and RESULT 1.5×10^{-10}

  '98 : 20 weeks $\Longleftarrow$ analysis ongoing

E787 data collection was completed.
expected sensitivity: $\sim 0.7 \times 10^{-10}$

byproduct modes: analysis under way

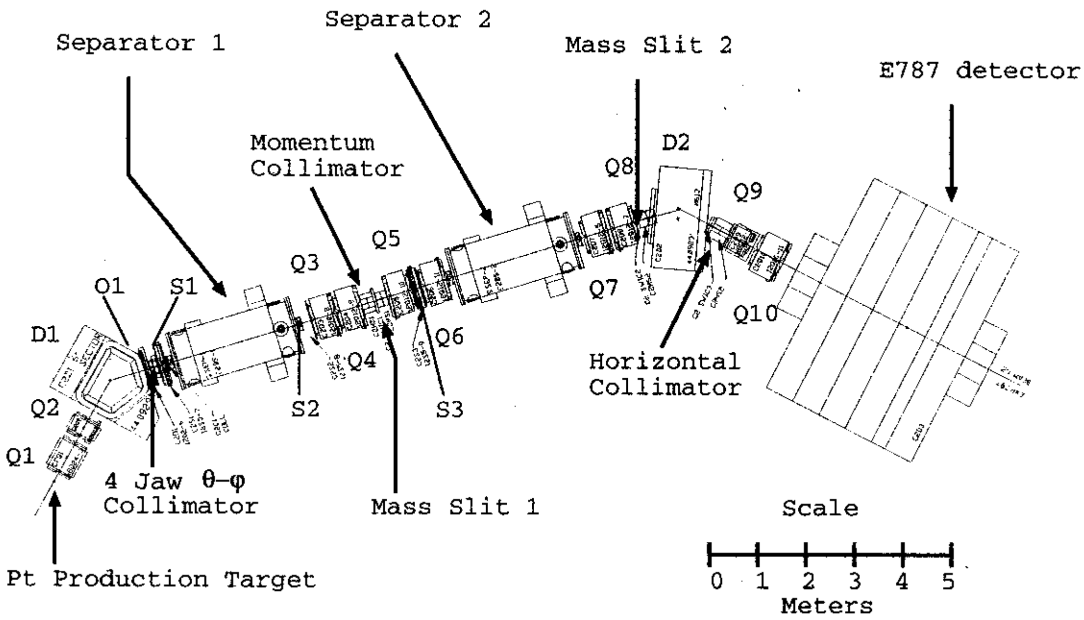


new result from '95-'97 Phy.Rev.Lett. 84, 3768 (2000)

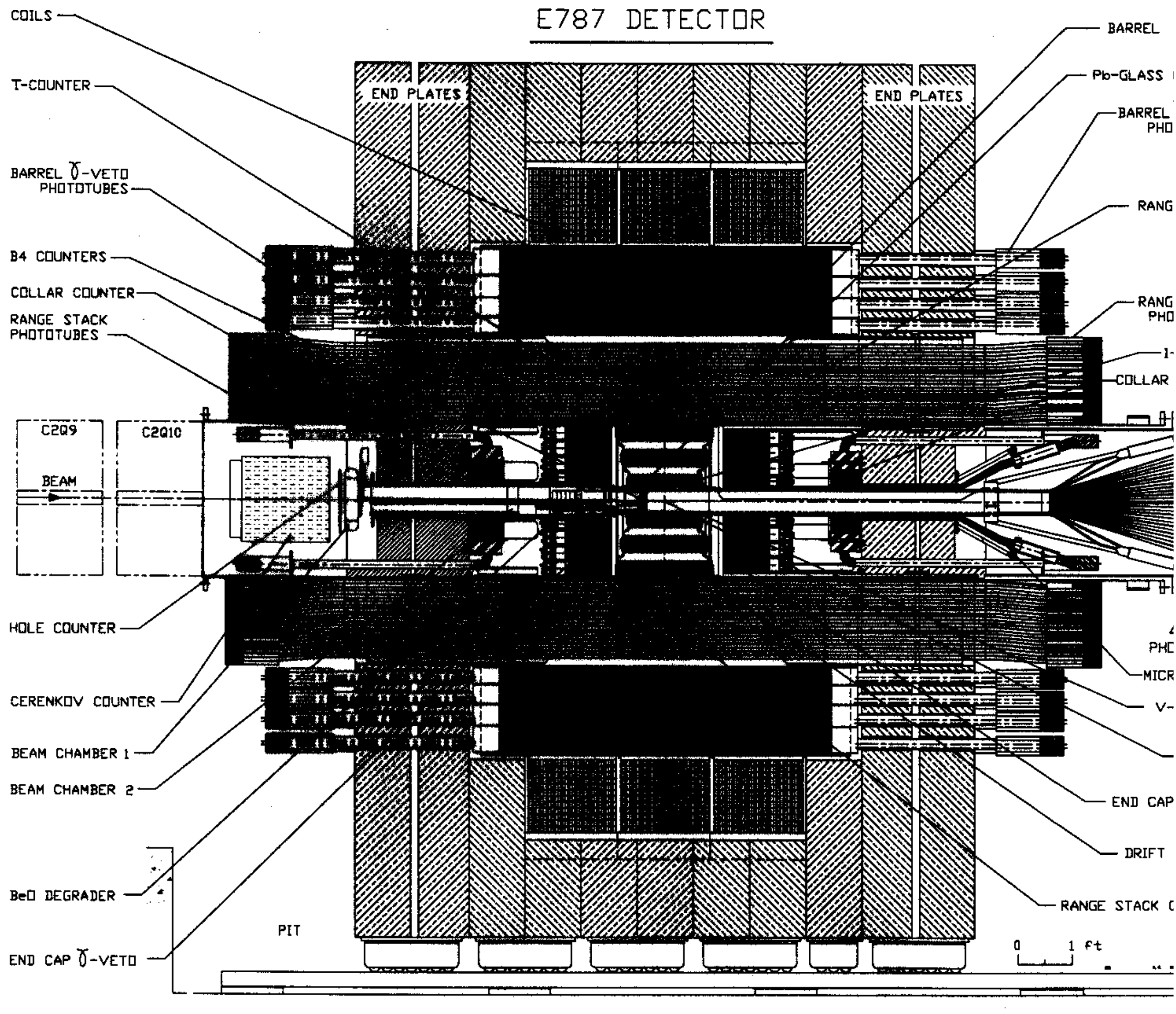
- branching ratio $(1.5^{+3.4}_{-1.2}) \times 10^{-10}$
- background level [0.08±0.02 events]: 1.2×10^{-11}
- $0.002 < |V_{td}| < 0.04$,
  $1.07\times10^{-4} < |V^*_{ts}V_{td}| < 1.39\times10^{-3}$
- consistent with the SM prediction

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

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



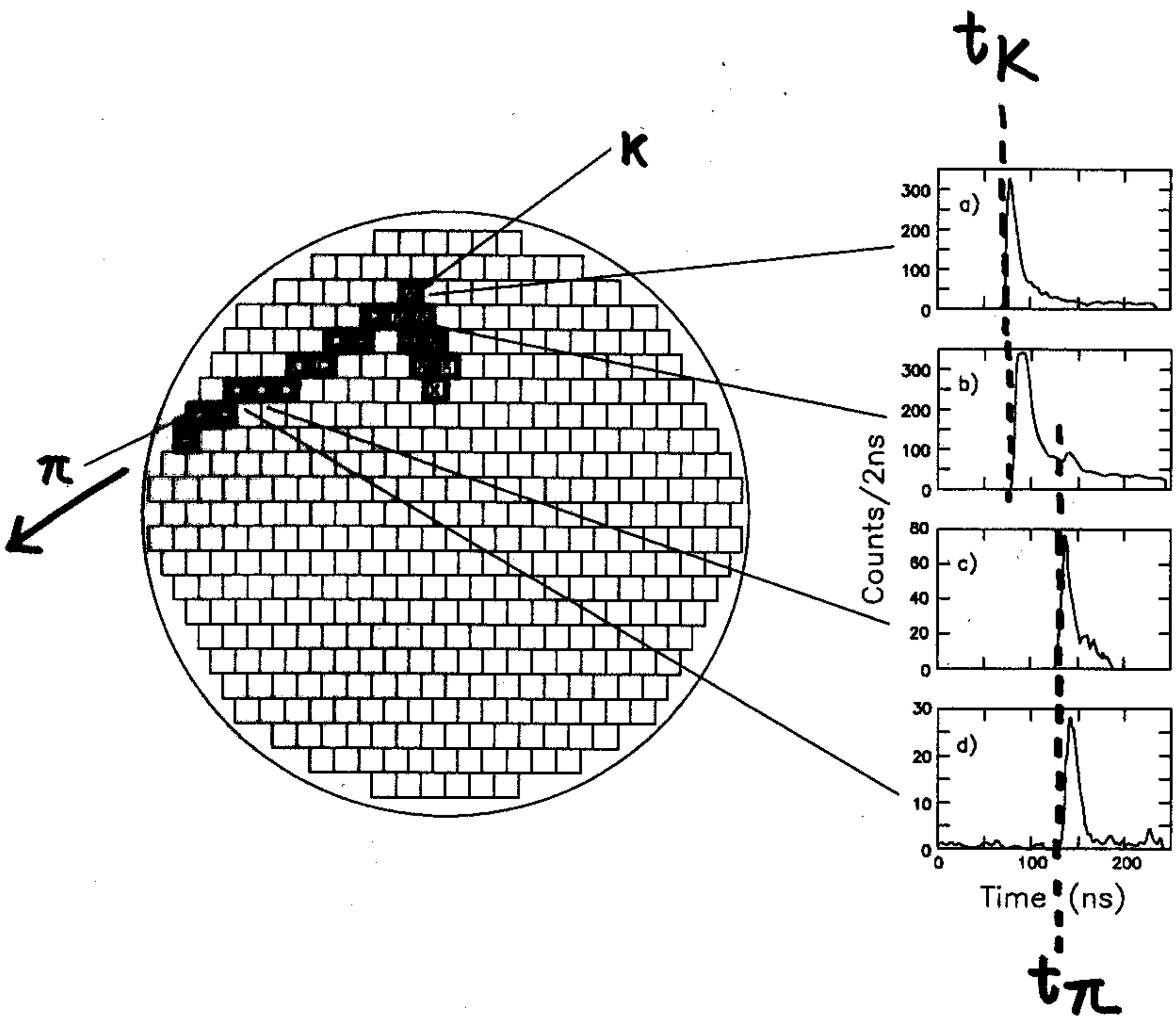
- $\sim 5 \times 10^5$ $K^+/10^{12}$ protons on target
- K/π ratio > 3



E787 DETECTOR
COILS
T-COUNTER
BARREL γ-VETO PHOTOTUBES
B4 COUNTERS
COLLAR COUNTER
RANGE STACK PHOTOTUBES
C2Q9
C2Q10
BEAM
HOLE COUNTER
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
BeO DEGRADER
END CAP γ-VETO
END PLATES
END PLATES
PIT
BARREL
Pb-GLASS
COLLAR
END CAP
DRIFT
RANGE STACK
0 1 ft

$K^+ \longrightarrow \pi^+$ Decay

- 5 mm × 5 mm scintillating fibers
- 500 MHz GaAs CCD digitizers

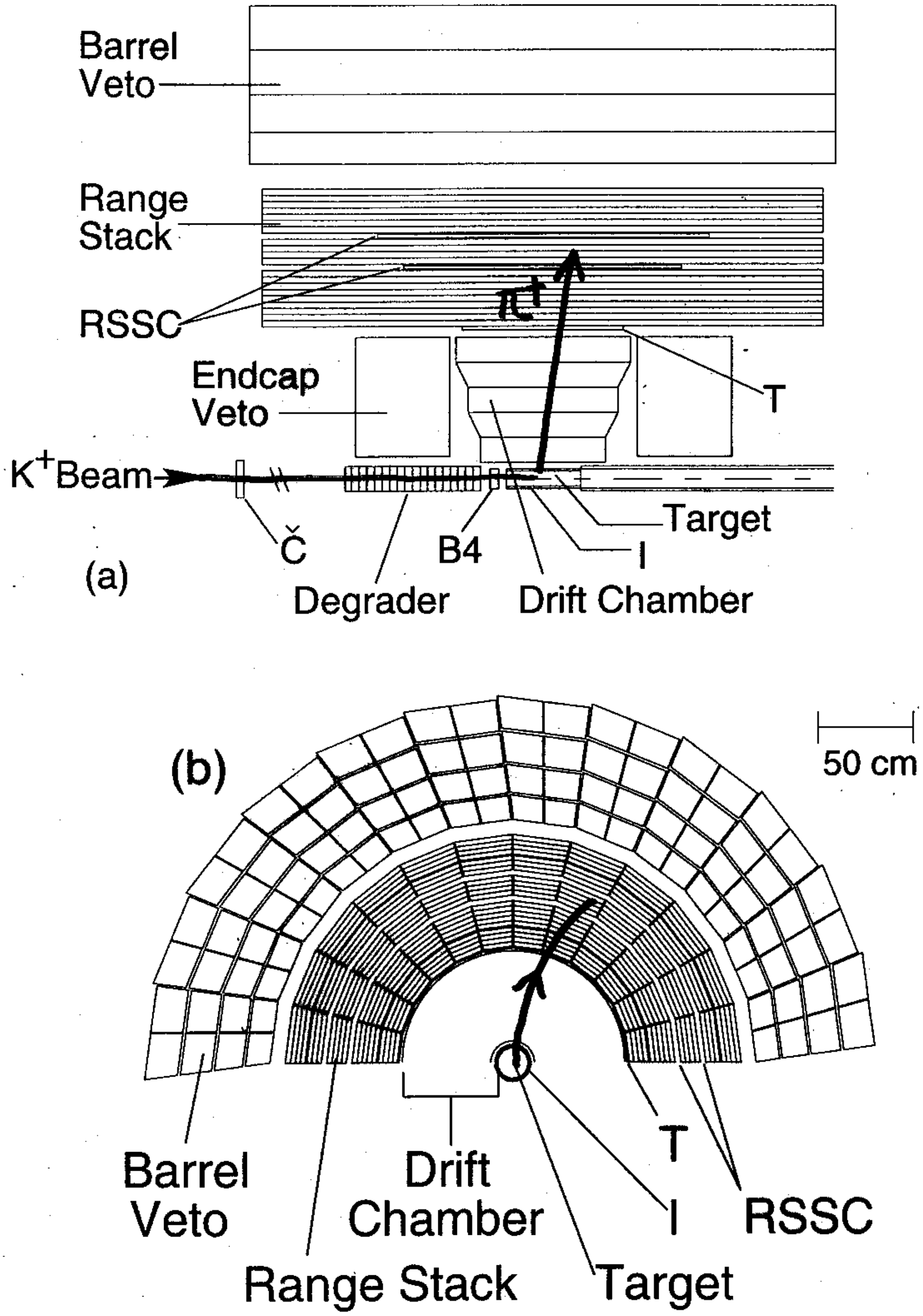


vs. **pions** or **kaon decay-in-flight** into the detector (π_{scat})
(Target, Beam counters/chambers)

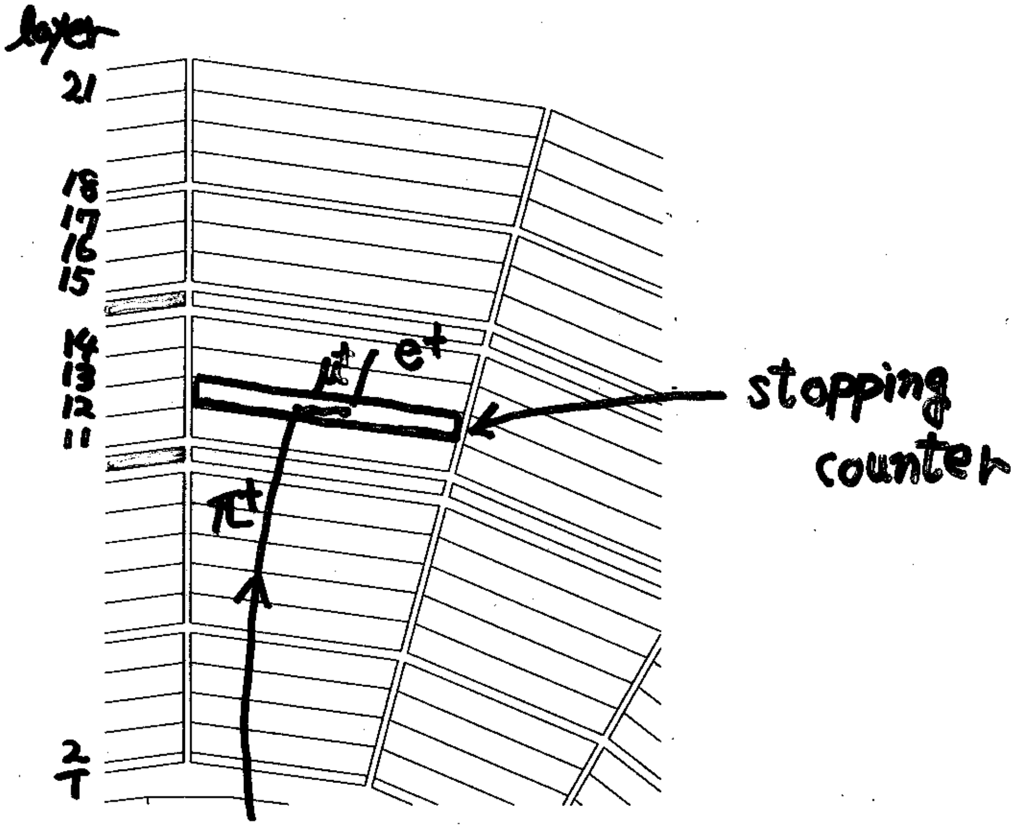
$t_\pi - t_K \geq 2^{nsec}$

[Delayed Coincidence]

E-787 Spectrometer



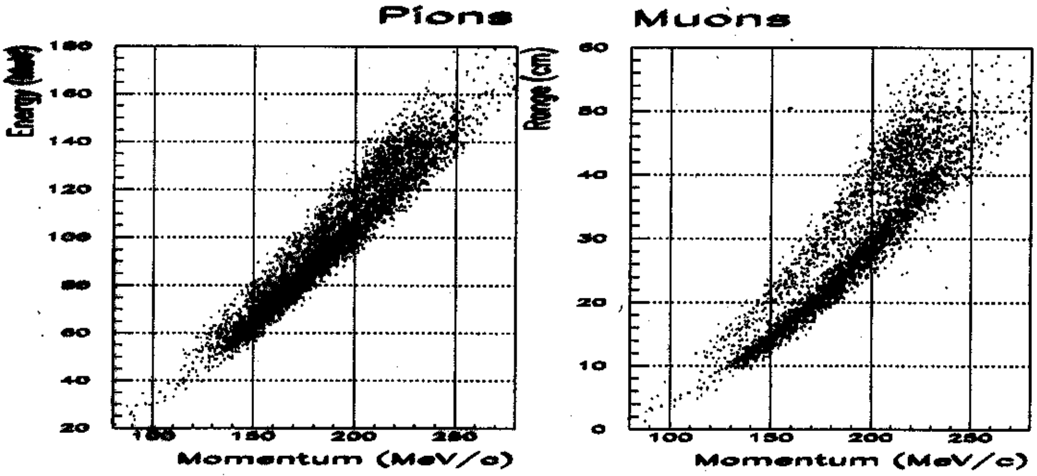
/memo/slides/seminar_97/spect.tex



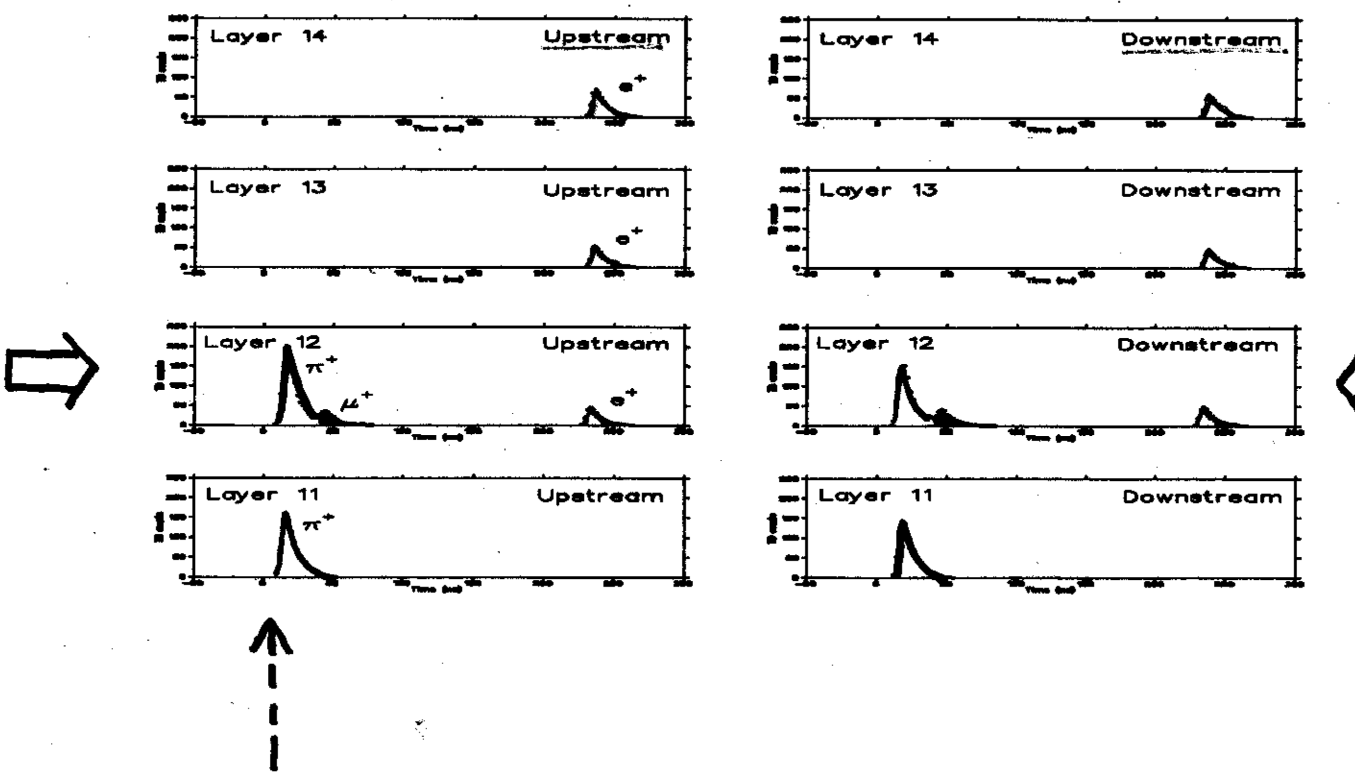
layer
21
18
17
16
15
14
13
12
11
2
1
μ^+
e^+
π^+
stopping
counter

vs. muons from $K^+ \to \mu^+\nu$, $K^+ \to \mu^+\nu\gamma$

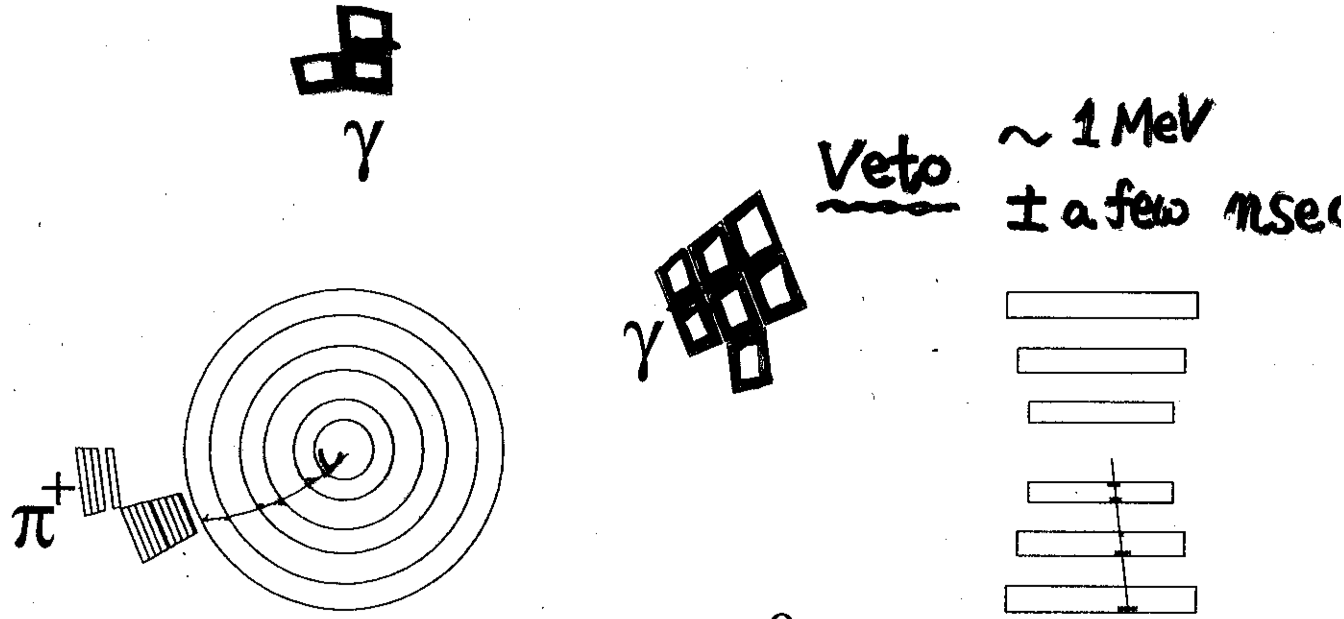
- Energy/Range - Momentum relation



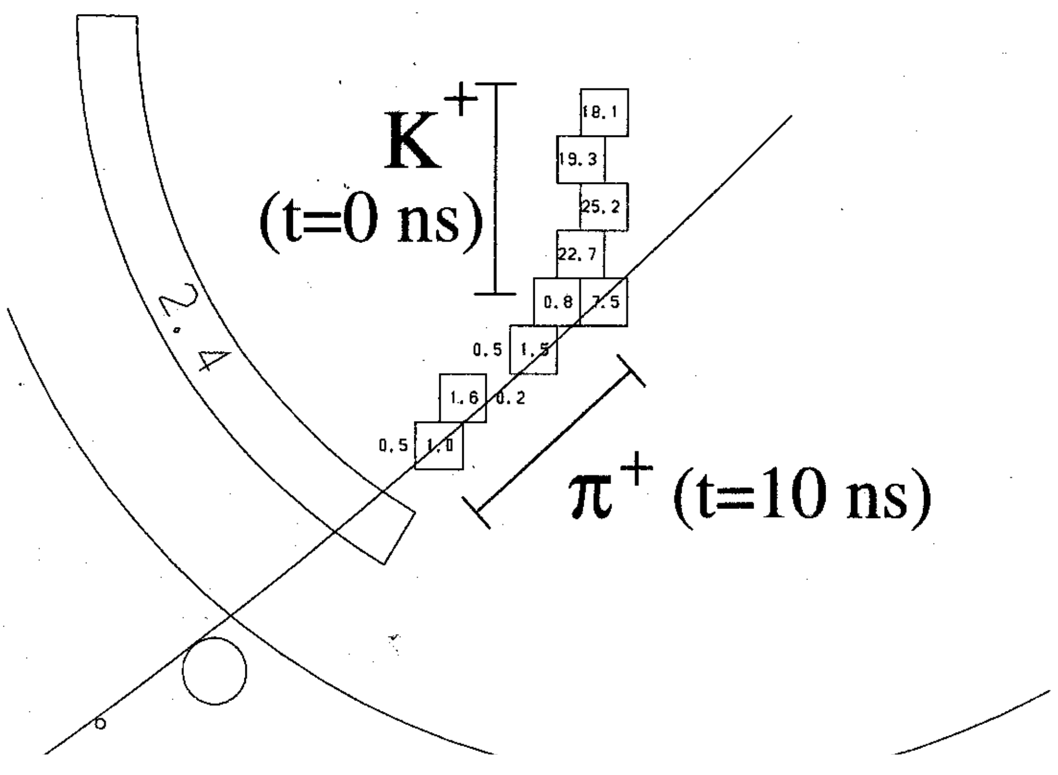
- $\pi^+ \to \mu^+ \to e^+$ chain (Transient Digitizer)

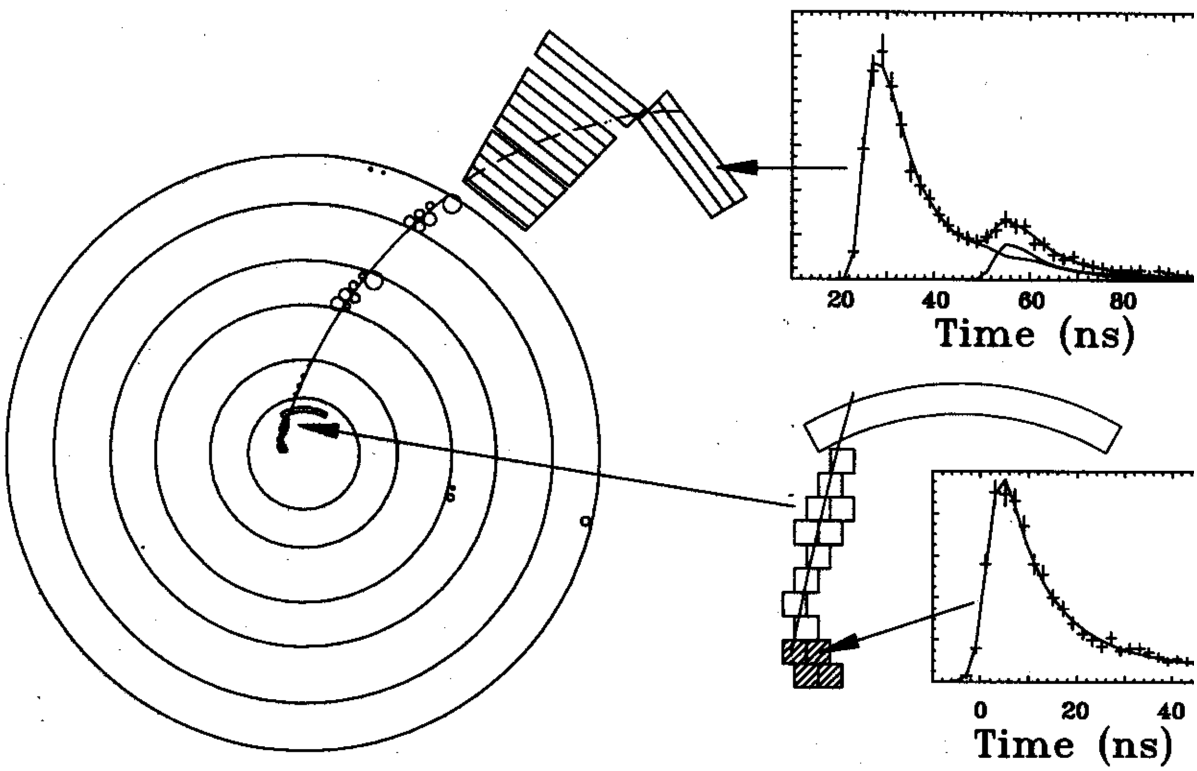


Typical Event



$$K^+ \to \pi^+ \pi^0$$
$$\pi^0 \to \gamma\gamma$$





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

S. Adler *et al.*, (E787 collaboration)

Phy. Rev. Lett. **79**, 2204 (1997)

'95 data [18 weeks]

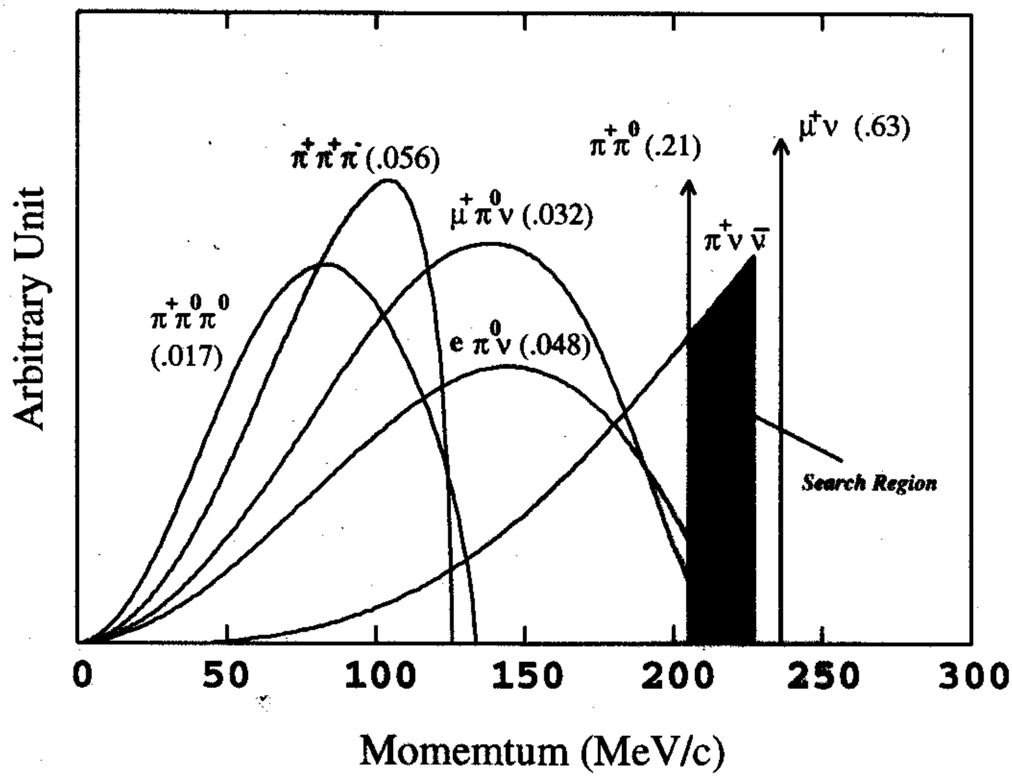
Why the $\underline{K^+ \rightarrow \pi^+ \nu\bar{\nu}}$ experiment is so "difficult" ?
(from my personal viewpoint)

or

Things that are NOT secret,
but you cannot easily learn
by reading the papers

$$\text{Acceptance} = 0.21_{\pm.01(\text{stat})\pm.02(\text{sys})}\%$$

Acceptance factors	method	
$K^+ \to \pi^+\nu\bar{\nu}$ phase space	M.C.	0.155
Solid angle acceptance	M.C.	0.407
π^+ nucl. int., decay-in-flight	M.C.	0.513
K^+ stop efficiency	BR($K_{\mu 2}$)	0.704
K^+ decay after 2 ns	$K_{\mu 2}$	0.850
Reconstruction efficiency	$K_{\mu 2}$	0.959
Other kinematic constraints	π_{scat},$K_{\pi 2}$	0.665
$\pi - \mu - e$ decay acceptance	π_{scat}	0.306
Beam and target analysis	$K_{\mu 2}$	0.699
Accidental loss	$K_{\mu 2}$	0.785
Total acceptance		0.21%



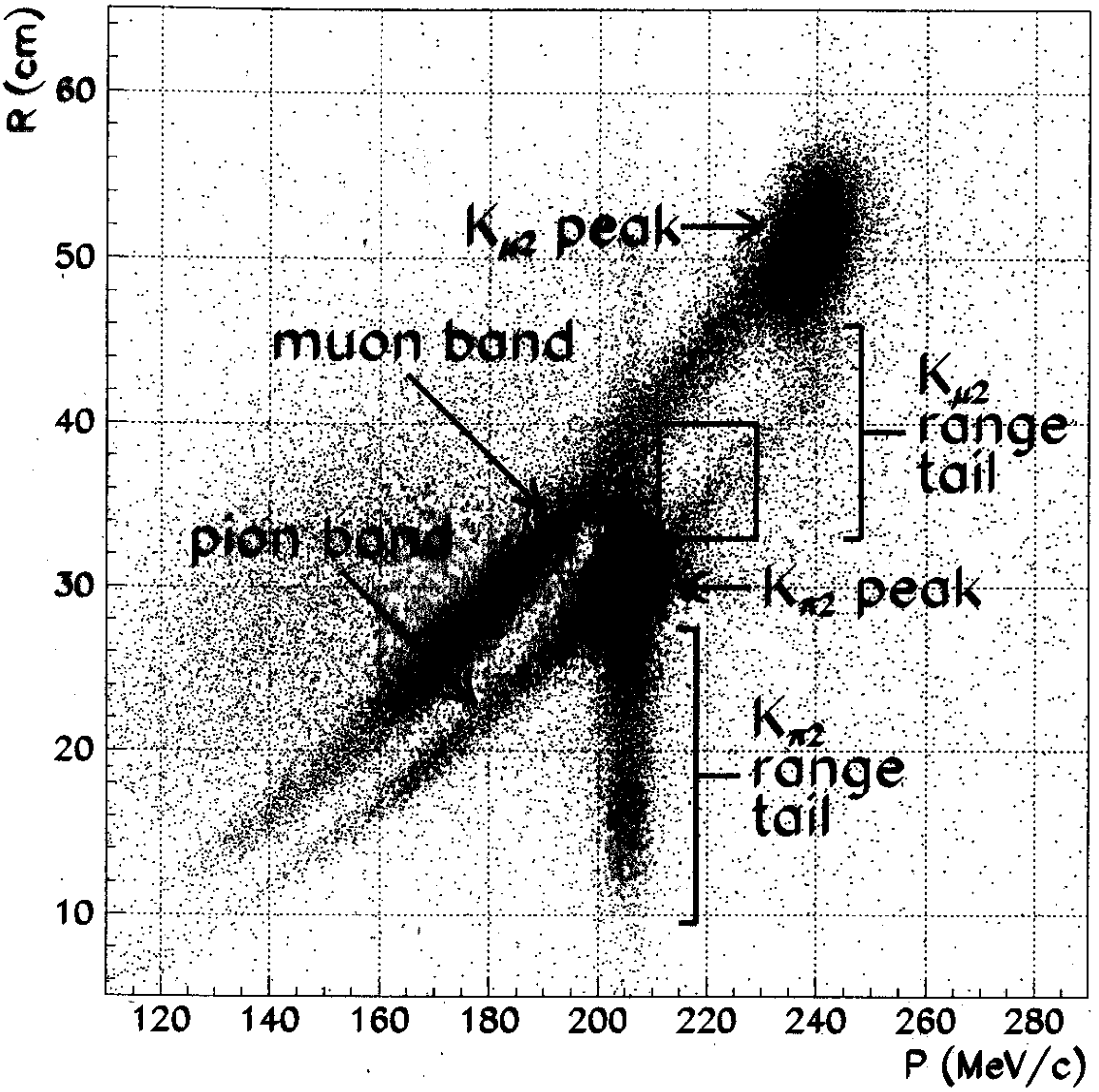
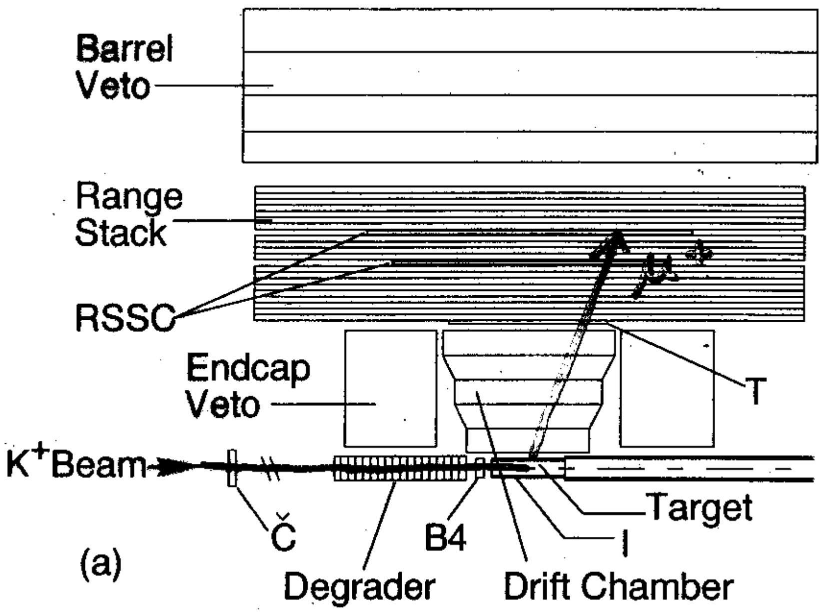


Figure 4.1: Range in scintillator (R) vs. momentum (P), and kinematic categorization of events passing the $K_{\pi 2}(1)$ trigger. The $\pi^+\nu\bar{\nu}(1)$ signal region is shown as a box. The $K_{\mu 2}$ peak momentum is reconstructed higher than the accepted value of 236 MeV/c [10] because a "pion hypothesis" has been used to calculate the momentum loss in the target (see section B.1).

- $K^+ \to \mu^+ \nu$ [$K\mu 2$] .63



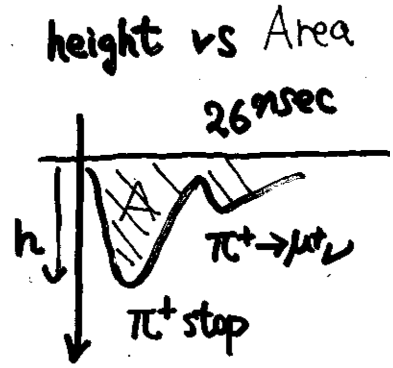
- μ^+ rejection { online / offline

μ^+ Rejection

[500MHz Transient Digitizers for RS]

tag $\pi^+ \to \mu^+ \to e^+$ decay chain by recording RS pulses

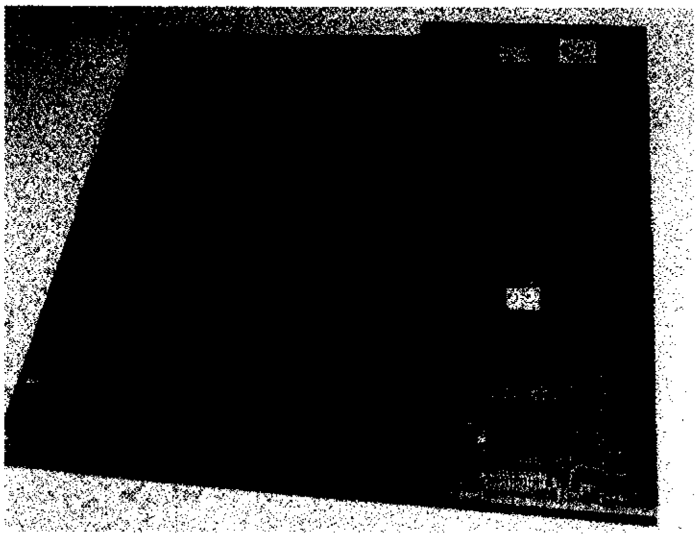
online trigger (tag $\pi^+ \to \mu^+$)
$\hookrightarrow$ Level 1.1 [hardware]



Control Board with ASIC's

(Application Specific Integrated Circuits)

$\Rightarrow$ decision time : $(150 \sim 250\mu s)_{L1.6}$ $\to$ 15-20 μs

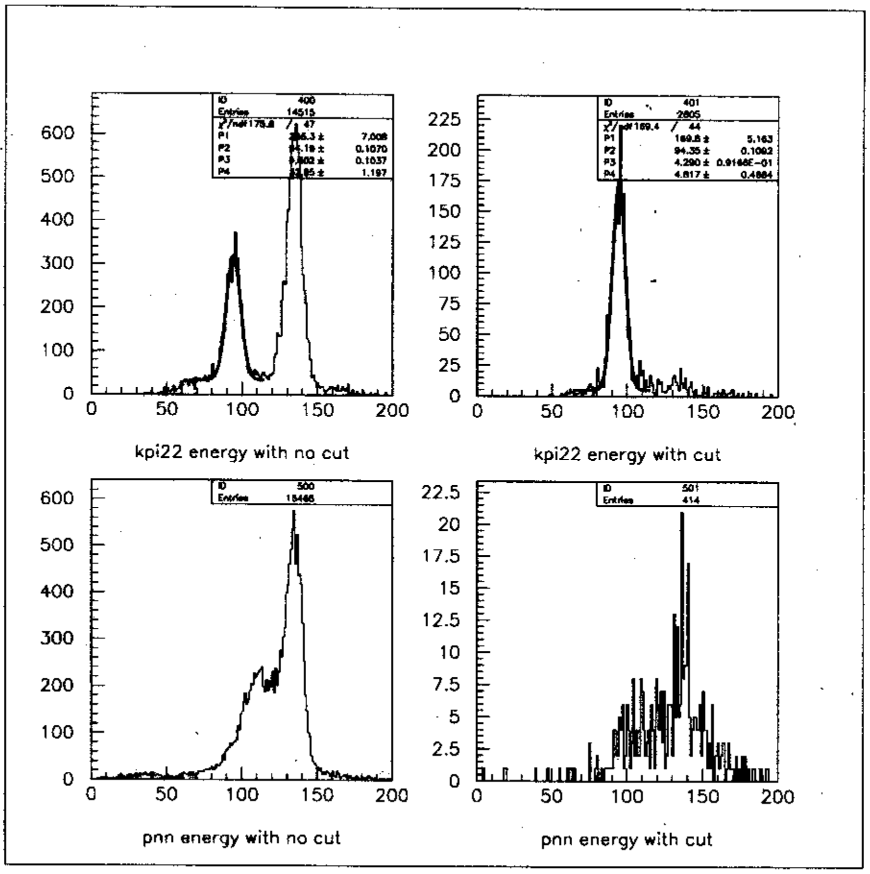


Level 1.1 Trigger Results

Without L1.1 cut   With L1.1 cut

$K_{\pi 2}(1)$ triggers

$\pi\nu\overline{\nu}1$ triggers

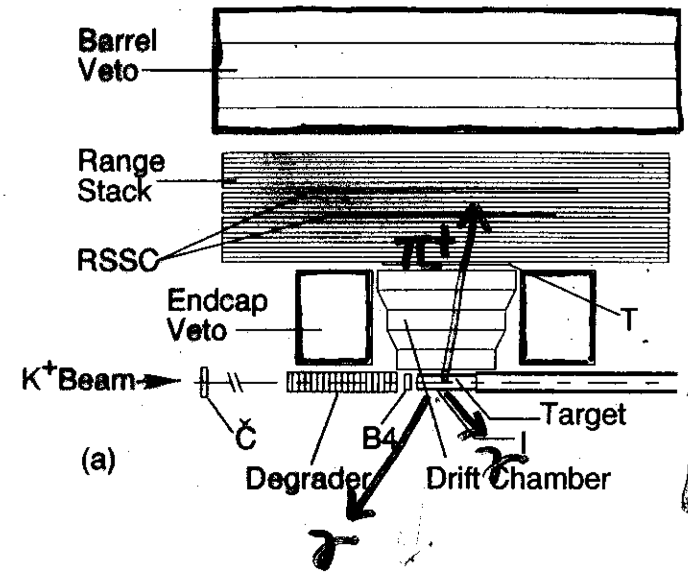


Kinetic energy charged track spectra with and without the l1.1 trigger cut for $K_{\pi 2}(1)$ and $\pi\nu\overline{\nu}1$ triggers

π^+ tagging efficiency $\sim 60\%$
μ^+ rejection factor $\sim 15-25$
Trigger Decision Time $\sim$ 10 $-$ 20 μs

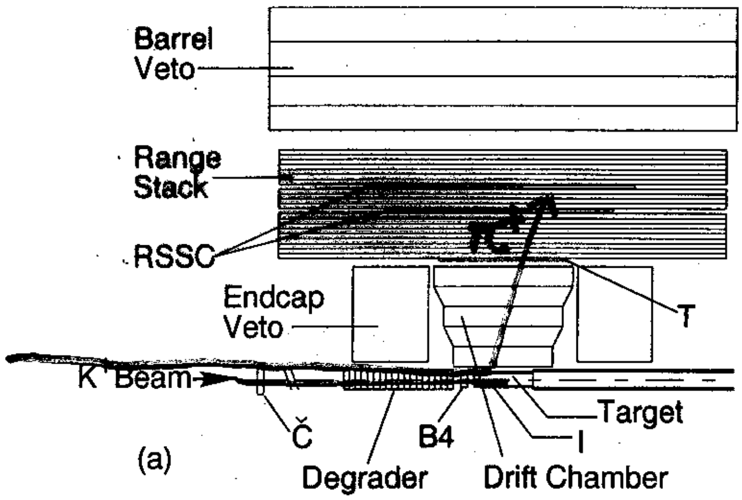
S. Adler

∘ $K^+ \to \pi^+ \pi^0$ [$K\pi 2$]



Photon Veto

∘ beam

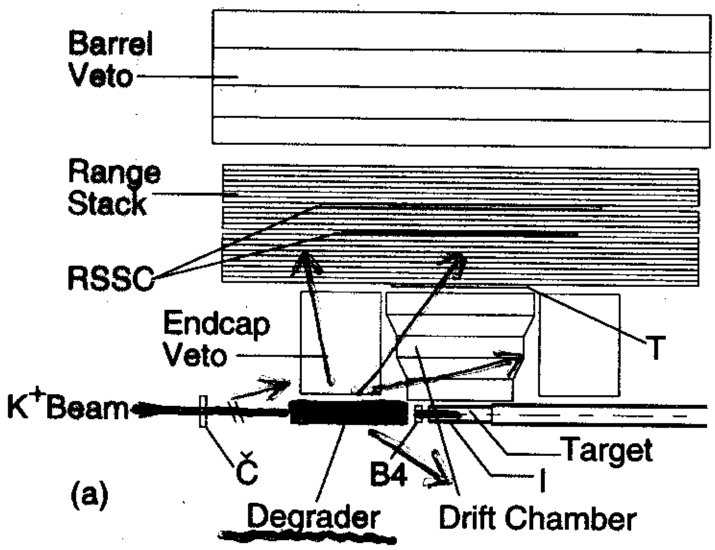


beam cuts

target cuts

Strategy of stopped K^+ experiment

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

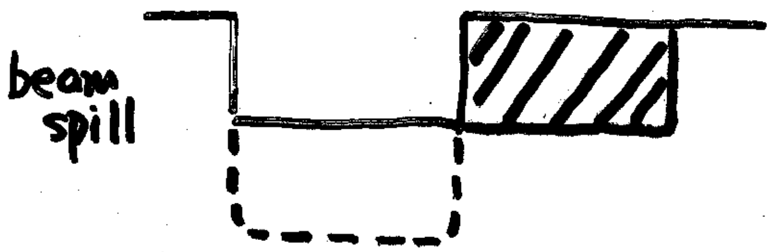


rate $\propto$ incident beam (not 'stopped K^+') :

the beam momentum ↘ (less degrader)

$\Longrightarrow$ K^+ stopping fraction ↗

- duty factor



• $K^+ \to \pi^+ \nu \bar{\nu}$

below the Kπ2 peak

(lower π+ momentum)

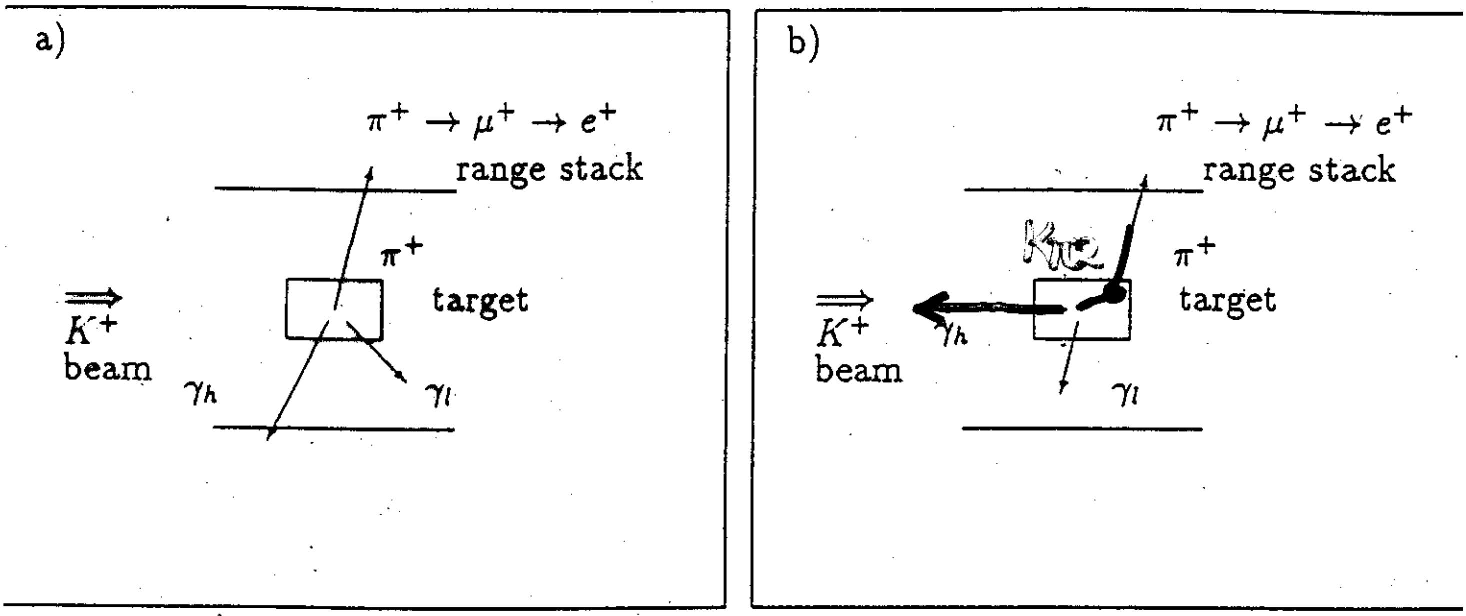


Figure 2: a) A typical $K_{\pi 2}$ event: π^+ enters into the range stack and two photons fr π^0 enters the photon detector. b) A $K_{\pi 2}$ background event in the region below $K_{\pi 2}$: that is produced to the beam direction enters the range stack after large angle scatter and the higher energy photon goes to the beam hole.

target analysis

PV systems

Interaction of $\pi^+/\mu^+/\gamma$ in the Target, Range Stack

In addition to

- Multiple Coulomb scattering (with non-Gaussian tail) of π^+/μ^+ and
- ElectroMagnetic shower of γ,
- π^+ hadronic interactions in plastic scintillator:

				σ(125MeV)
elastic	$\pi^+\ {}^{12}C$	$\rightarrow$	$\pi^+\ {}^{12}C$	214 mb
pseudo-elastic	$\pi^+\ {}^{12}C$	$\rightarrow$	$\pi^+\ {}^{12}C^*$	11 mb
quasi-elastic	$\pi^+\ {}^{12}C$	$\rightarrow$	$\pi^+\ p\ {}^{11}B^{(*)}$	52 mb
	$\pi^+\ {}^{12}C$	$\rightarrow$	$\pi^+\ n\ {}^{11}C^{(*)}$	31 mb
	$\pi^+\ {}^{12}C$	$\rightarrow$	π^0 N X	16 mb
absorption	$\pi^+\ {}^{12}C$	$\rightarrow$	X(withoutπ)	194 mb
spallation	$\pi^+\ {}^{12}C$	$\rightarrow$	π^+ X	120 mb

- μ^+ elastic/inelastic scattering:
  - hard scattering
  - $\mu^+\ {}^{12}C$ Giant Dipole Resonance
- Photo-nuclear absorption

Cross section, energy loss, scattering angle, ... are unknown/uncertain to the low-energy particles from stopped-kaon decays.
We cannot rely on Monte Carlo;
we need to work on and learn from data.

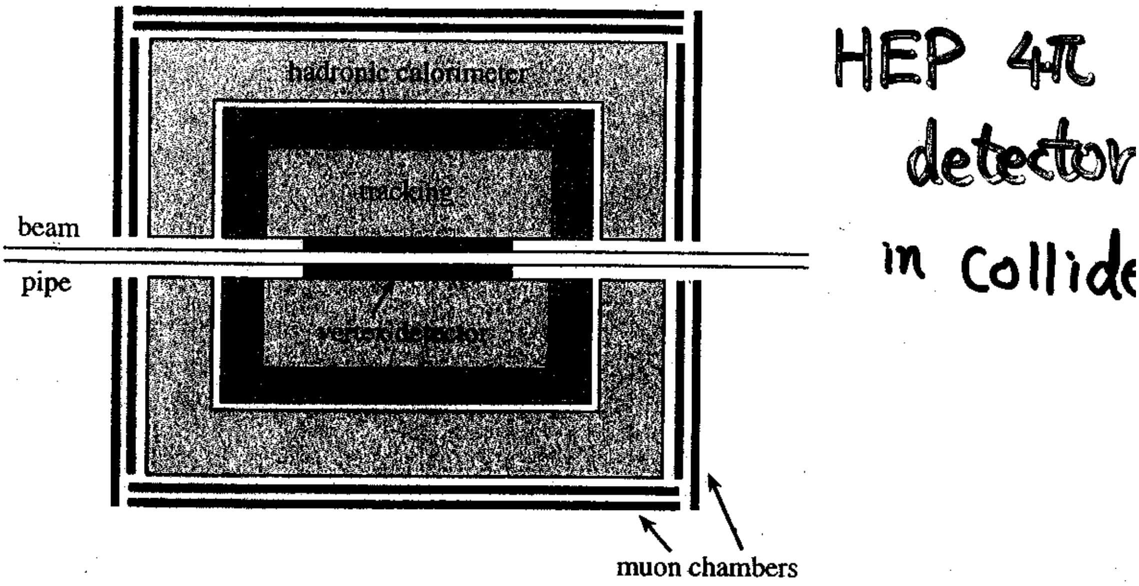
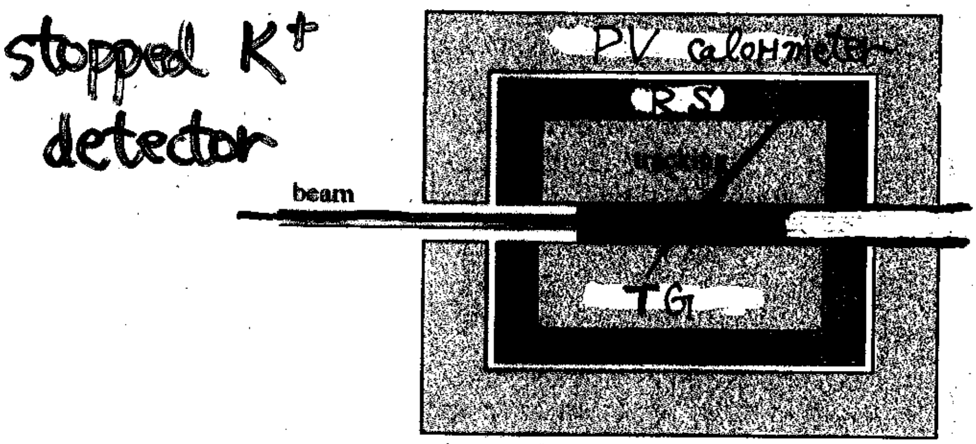
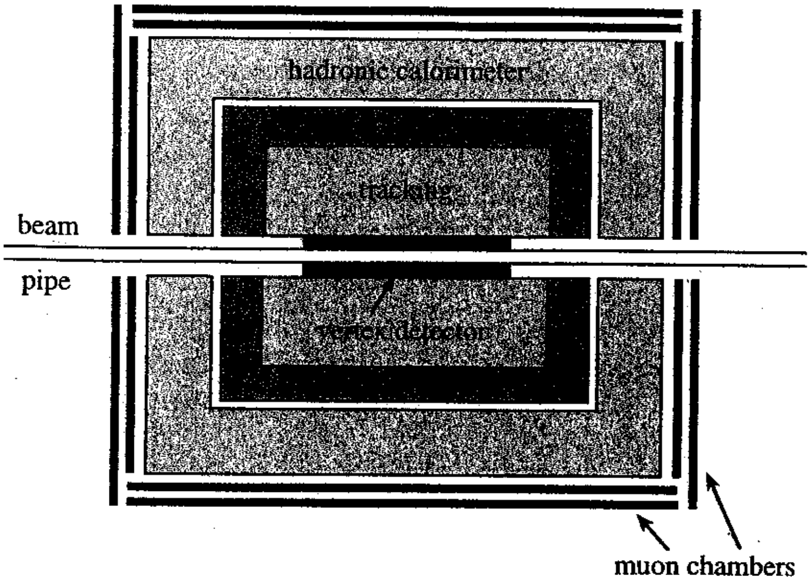


Figure 4: Schematic cross section through a typical collider detector. Shown, from the beam pipe out, are the locations of vertex detector, tracker, electromagnetic calorimeter, hadronic calorimeter, and muon chambers.





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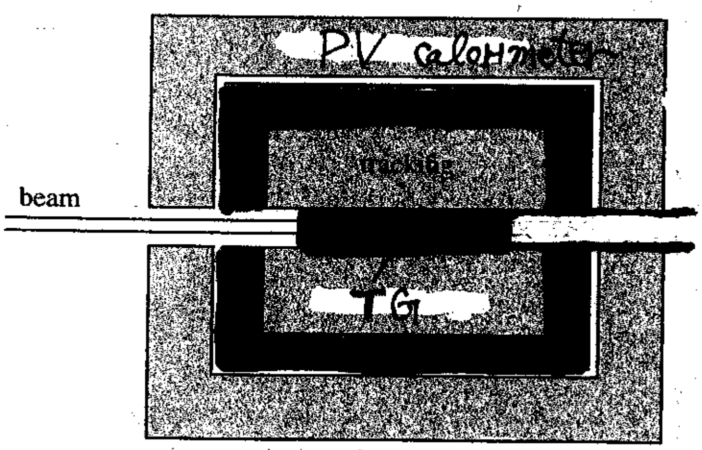

① π^+/μ^+ non-destructive measurement in (destructive) TG, RS

② three timings (t_π, t_μ, t_e) <wait these decays> ← accidental loss

③ waveform digitization ← huge event size

E949

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

P. Kitching and H.-S. Ng

Centre for Subatomic Research, University of Alberta

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

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A. Kozjevnikov, L. Landsberg, V. Mukhin, V. Obraztsov, S. Petrenko, V. Rykali
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B. Bassalleck, D.E. Fields, J. Lowe and T.L. Thomas

University of New Mexico (UNM)

T. Nakano and M. Nomachi

Research Center for Nuclear Physics (RCNP), Osaka University

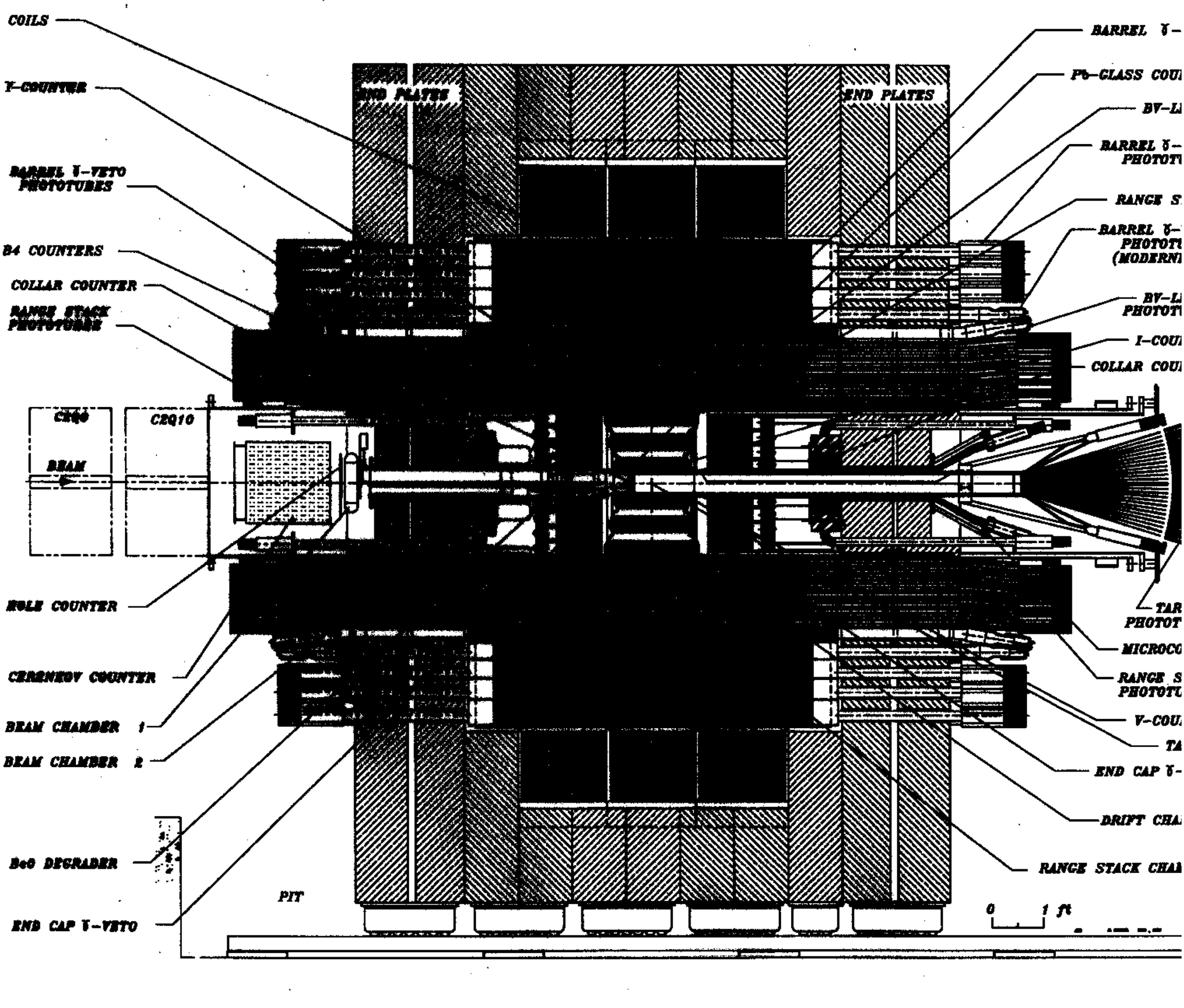
P.C. Bergbusch, E.W. Blackmore, D.A. Bryman, S. Chen, A. Konaka, J.A. Macdon
J. Mildenberger, T. Numao, J.-M. Poutissou and R. Poutissou

TRIUMF

E949

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

Alberta/UBC/FNAL/IHEP/INR/Kyoto/UNM/Yeshiva
BNL/Fukui/KEK/Osaka/TRIUMF

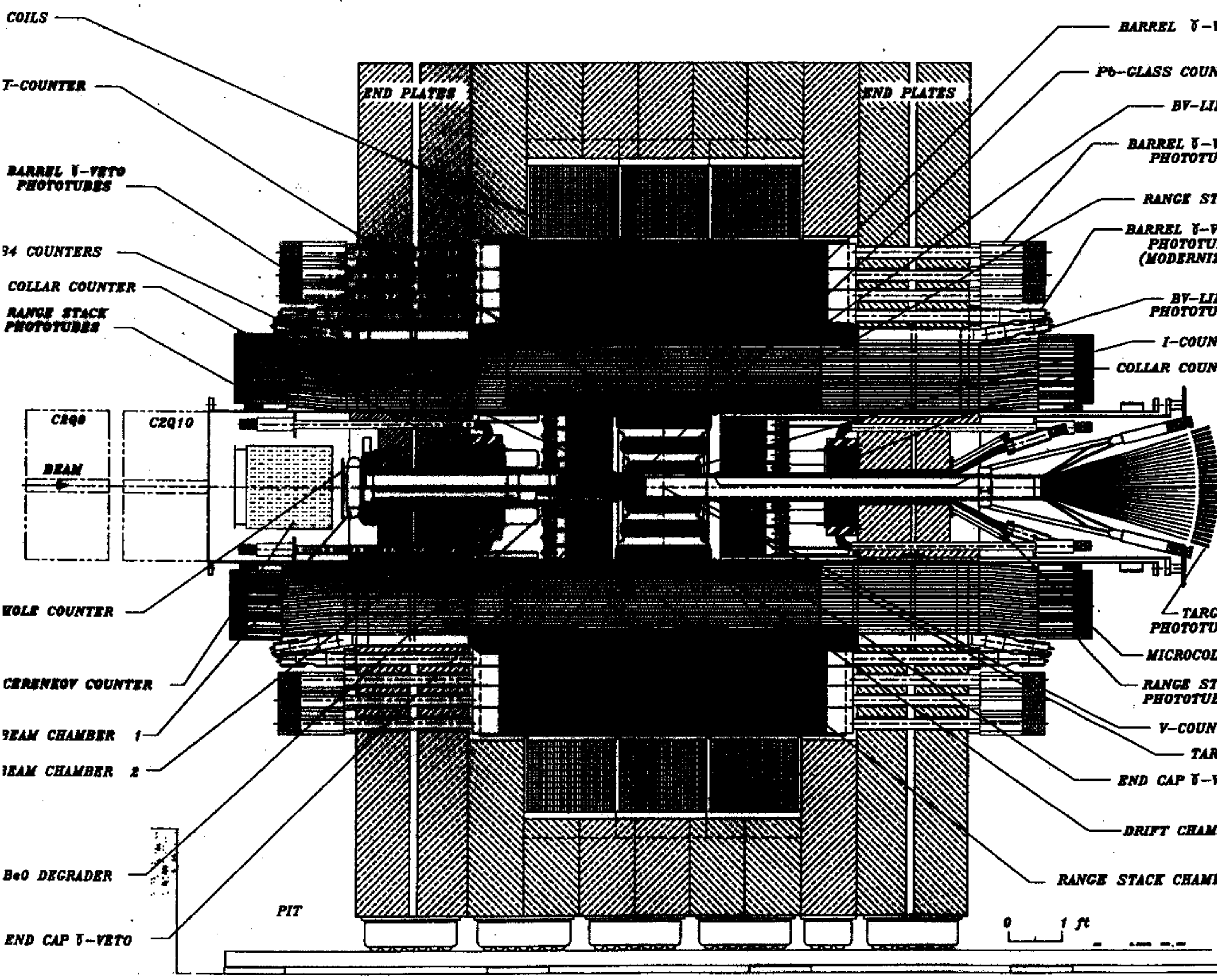


E949

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

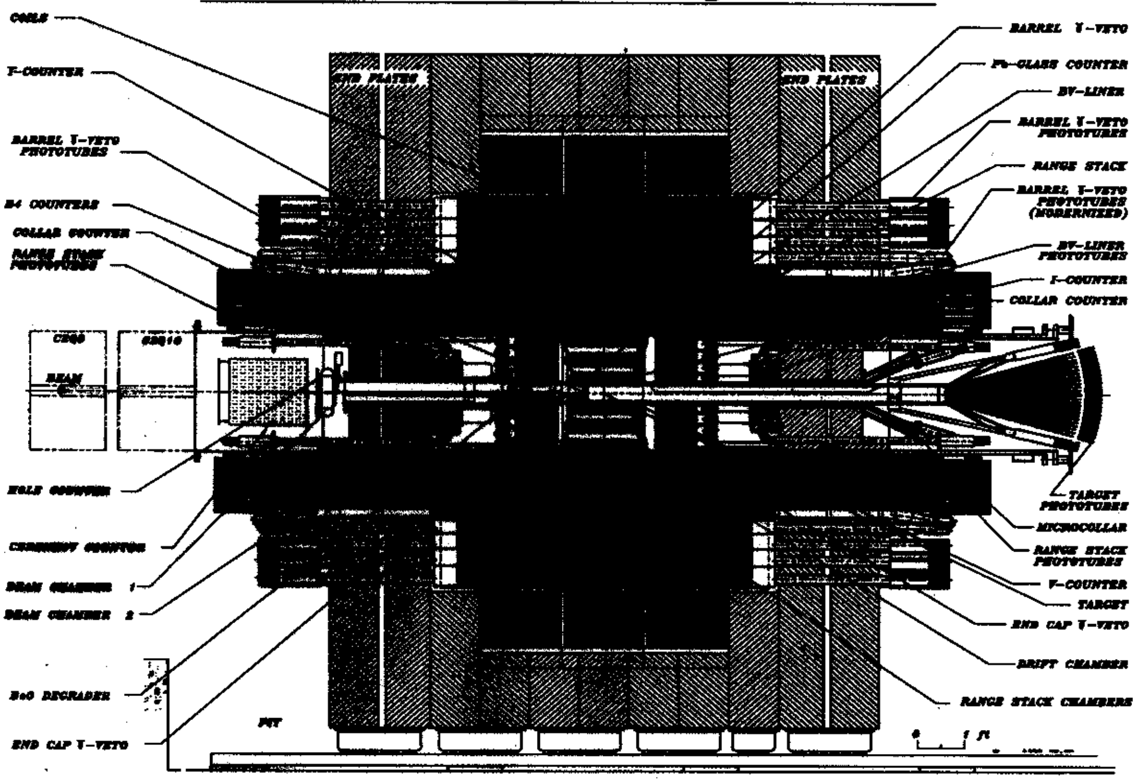
Alberta/UBC/FNAL/IHEP/INR/Kyoto/UNM/Yeshiva
BNL/Fukui/KEK/Osaka/TRIUMF

- **BV Liner**



- **RS** (Layer T, 2 ~ 5)
- **PV**
- **BM**

E949 `www.phy.bnl.gov/e949/`



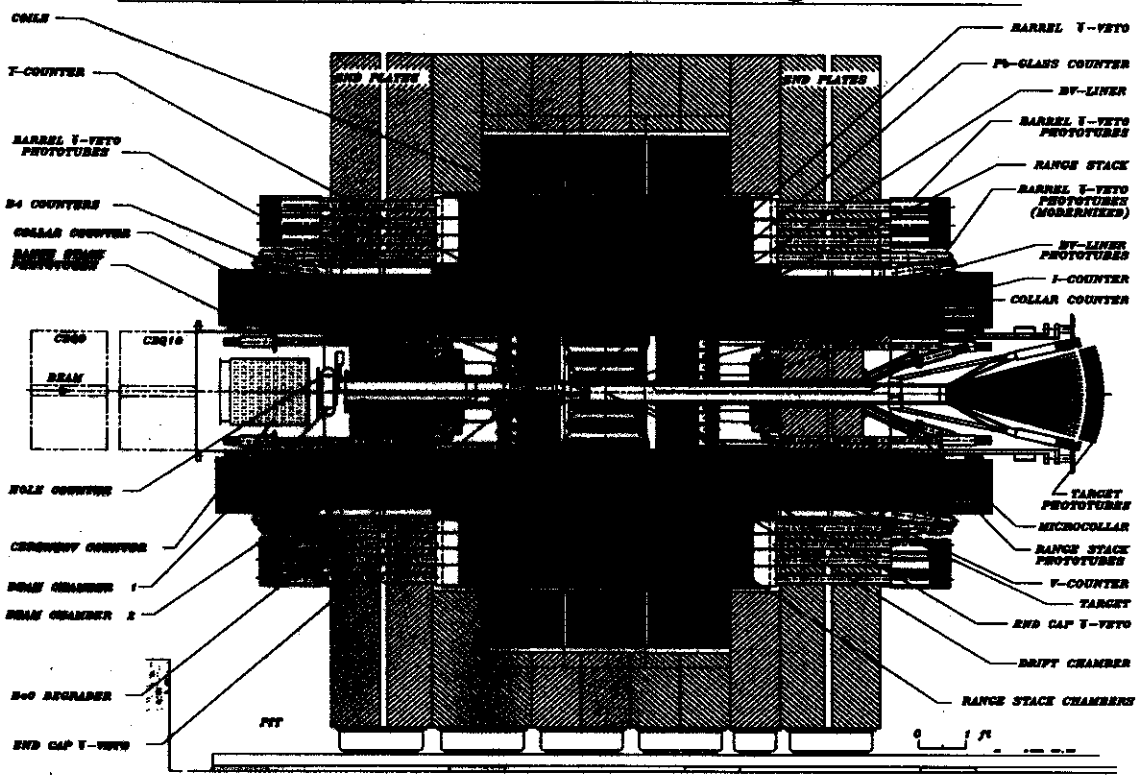
Detector upgrade from E787

- BV Liner
- RS: layerT,2∼5 replaced
- PV: new/improved counters
- BM: new B4 counter, degrader
- Trigger: programable Level0 board, Mean Timers
- DAQ
- RS Monitor system using LEDs
- RS TDC readout: e^+ identification without TD
- ...

Schedule:

- Engineering run from this spring.
- First Physics run in this summer/autumn/winter (with RHIC).

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



Sensitivity Improvement (compared to the published '95-97 result of E787)

- Running mode :
  - stopping fraction (×1.1)
  - high duty factor with 65Tp from AGS (×1.4)
  - beam hours: ∼ 2 years of running with RHIC (×1.5)
- Apparatus (trigger, DAQ, software, ...):
  - efficiency improvements (×2.1)
- reoptimize analysis or increase the phase space (×2)
- Total gain of ×10

Goals:

- Sensitivity (8–14)$\times10^{-12}$ in 6000 hr (∼2 years of running with RHIC).
- Determine $|V_{td}|$ to 20–5%.

The furure

targetting

Sensitivity 1.0×10^{-12}
or $\sim$ 100 signal events
or the BR measurement with 10%

around the year 2010

Two options :

1. In-flight Kaon decay
   CKM Experiment at FNAL
   (talk by B. Tschirhart, in Special Session)
   $\Leftarrow$ The technique is not proved yet.
2. Stopped Kaon decay
   Can we further improve the E949-type detector
   in a JHF experiment
   and compete with CKM ??

Key 1: K$^+$ Beam

The JHF-50GeV Slow-Extraction is not optimized to the stopped $K^+ \to \pi^+ \nu \bar{\nu}$ experiment.

PS operation		AGS to LESB3 for E949	JHF-mod to K550 (pnnJHF)	[1/3]
proton energy	GeV	24	30	
protons on Tgt	10^{12}/spill	65	100	× 1.54
machine cycle	sec	6.4	3.42	× 1/1.
average current	μA	1.63	4.68	× 2.88
slow extraction	sec	4.1	1.8	× 1/2.
duty factor		0.64	0.53	× 0.83
instant. rate	10^{12}/sec	16	55.6	× 3.5
K$^+$ momentum	MeV/c	730	550	(no lose
stopping fraction		0.26	0.4	× 1.5

Key 2: Detector

The upgrade of (destructive) Target and Range Stack (better measurement, rate capability)

- RS segmentation (chopping : < 1/4)
- scintillator/SCF readout with more light outputs

start Conceptual Design,
based on the E787/E949 experience.

stopped $K^+ \to \pi^+\nu\bar{\nu}$ experiment at JHF

Improvement (compared to the BNL-E949 proposal)

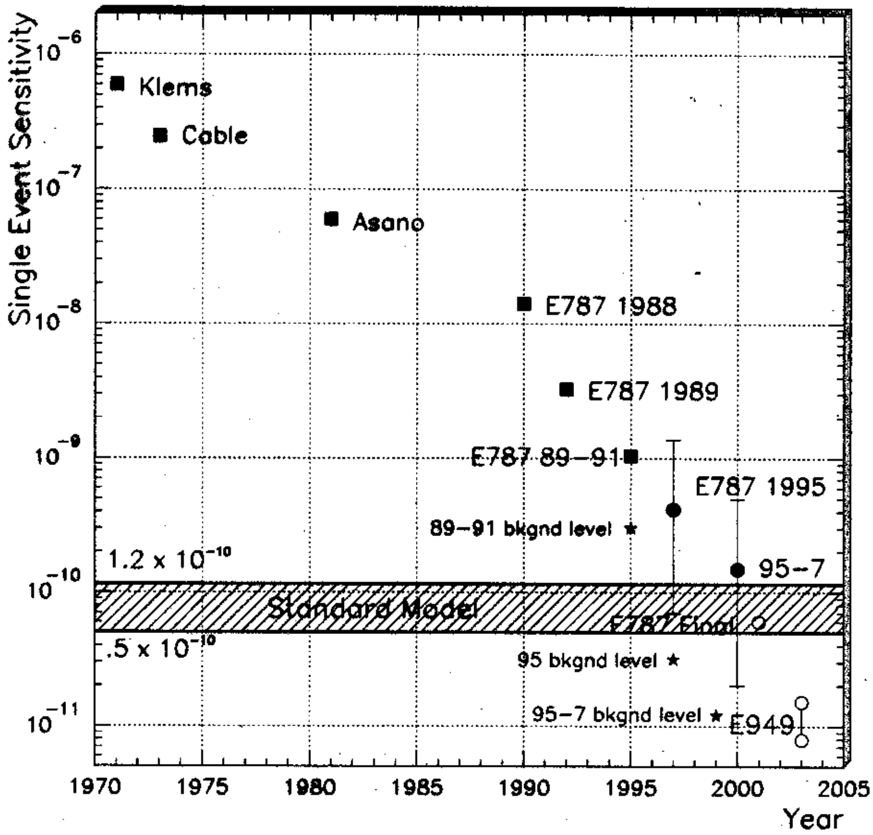
- Running mode :
  - stopping fraction ($\times$1.5 by K550)
  - duty factor ($\times$0.83)
  - beam hours : $\sim$3 years of running ($\times$1.5)
- New Detector [segmented, faster, ...] :
  - rate capability for higher intensity ($\times$2.0)
- re-optimization ($\times$1.5)
  - S/N = 5 $\Rightarrow$ TD electron cut, ... ($\times$1.2)
  - brighter detector $\Rightarrow$ better E resoluton, ... ($\times$1.2)
  - pipeline trigger, faster DAQ, ... ($\times$1.1)
- increase the phase space:
  $K^+ \to \pi^+\nu\bar{\nu}$ below the $K_{\pi 2}$ peak ($\times$2)
  and measure the π^+ spectrum to confirm the SM prediction.

Goals:

- Sensitivity 1 $\times 10^{-12}$ (Background 2 $\times 10^{-11}$)
- $\sim$ 100 SM signals , S/N = 5.
- competition with the "in-flight" experiment

Summary

$K^+ \to \pi^+\nu\bar{\nu}$ in the stopped-kaon experiment



- Not an easy job, but
  the stopped-kaon experiment is currently the best method to observe the $K^+ \to \pi^+\nu\bar{\nu}$ decay.
- BNL-E787 in '95-'97 : $(1.5^{+3.4}_{-1.2}) \times 10^{-10}$, and
  the expected sensitivity: $\sim\ 0.7 \times 10^{-10}$;
  still consistent with the SM and with beyond_the_SM.
- The new BNL-E949 experiment is rising, and
  starts takin data this year, and
  R&D issues for pnnJHF will be intensively studied.