BNL E949 collaboration

> 60 physicists, 15 institutes from Canada, Japan, Russia and the US.

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E949 institutes

- Japan: KEK(+Tokyo), RCNP, Fukui, Kyoto, Osaka, NDA
- US: BNL, FNAL, Stony Brook, New Mexico
- Canada: TRIUMF, Alberta, British Columbia
- Russia: IHEP, INR

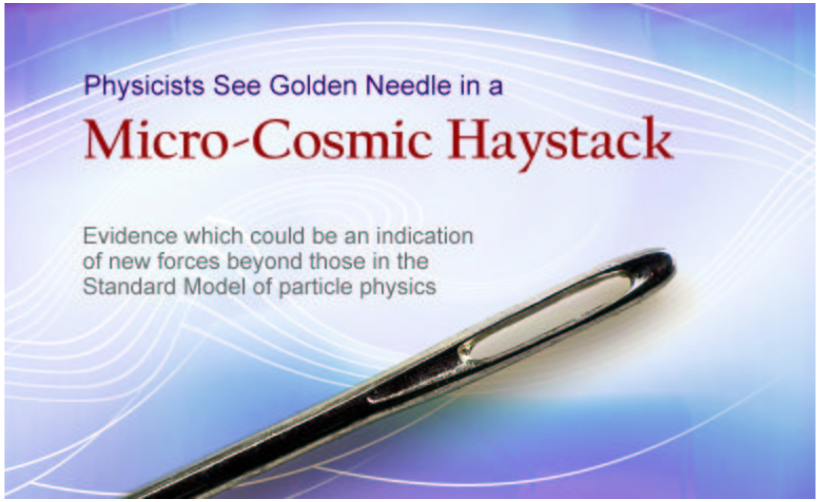
BNL-E787 (-1998)
proposed (1998), approved (1999)
construction/upgrade (-2001)
engineering run (2001)
First Physics Run (2002)

First Results from BNL-E949 on the Rare Decay $K^+ \to \pi^+ \nu \bar{\nu}$

Takeshi K. Komatsubara (KEK-IPNS)

representing the E949 collaboration

- `arXiv:hep-ex/0403036`
- JPS talk on March 28 by T.Sekiguchi (KEK & U.Tokyo)

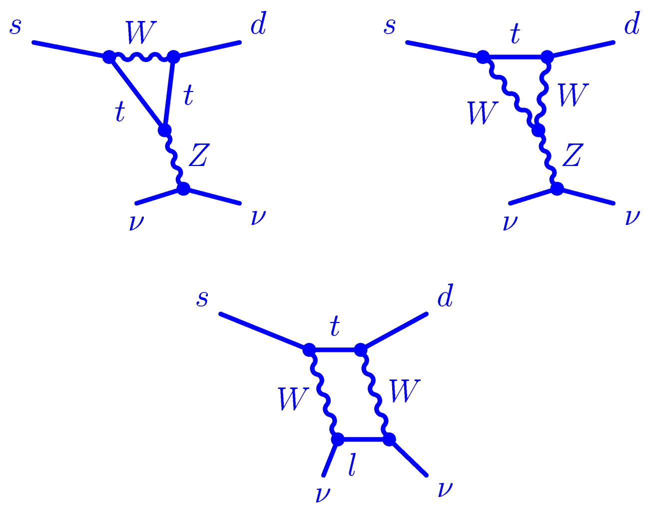


KEK Physics Seminar, April 7, 2004

Outline [in the next 51 slides, 50 minutes]

- $\mathbf{K^+ \rightarrow \pi^+ \nu \bar{\nu}}$:
  physics in and beyond the Standard Model
- E949 experiment in 2002: beam and detector
- Analysis: Likelihood Ratio Technique
  Confidence Level computation in Searches with Small Statistics
- Results
- Conclusions, and Future

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



- Standard Model:
  $s \rightarrow d$ FCNC loop $(W^{\pm}/Z^0)$
- top-quark (174 GeV/c^2) dominant
- $\lambda_t \equiv V_{ts}^* \cdot V_{td}$

  $= -A^2\lambda^5 \cdot (1 - \rho - i\eta)$:

  best place to determine $|\lambda_t|$ (or $|V_{td}|$)
- theoretical uncertainty $\sim 7\%$

Cabibbo(1963)-Kobayashi-Maskawa(1972) matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} .975 & .22 & .002 - .005 \\ .22 & .974 & .038 - .044 \\ .004 - .014 & .037 - .044 & .999 \end{pmatrix}$$

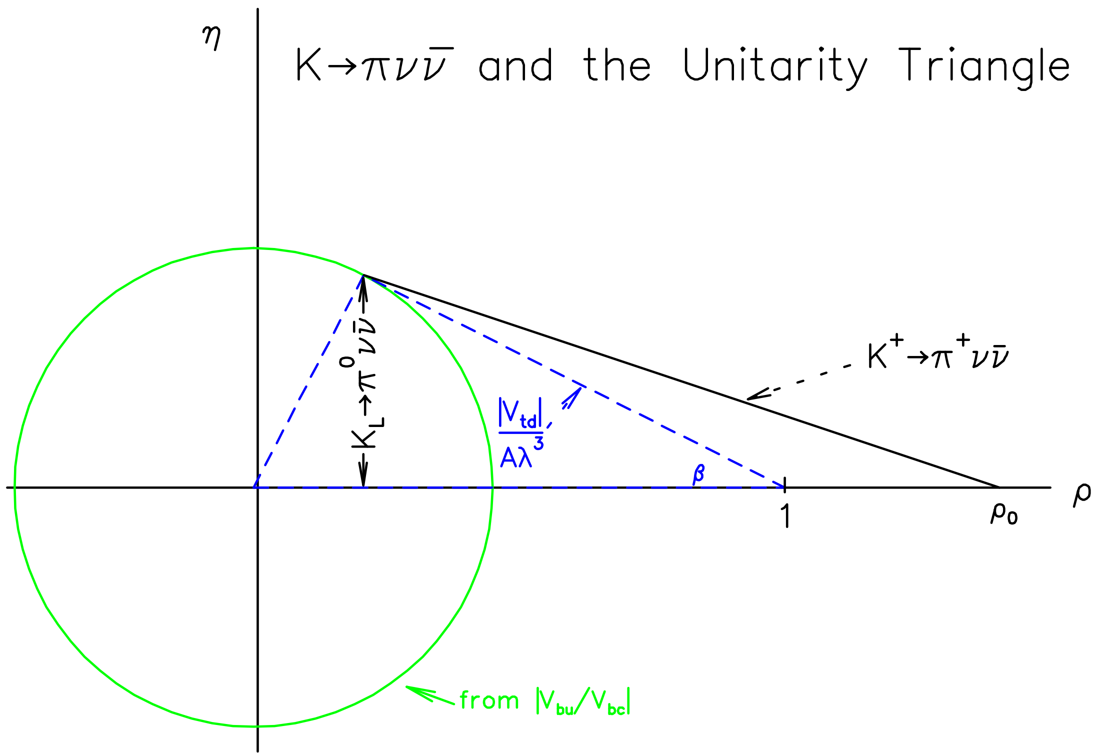
$$\simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

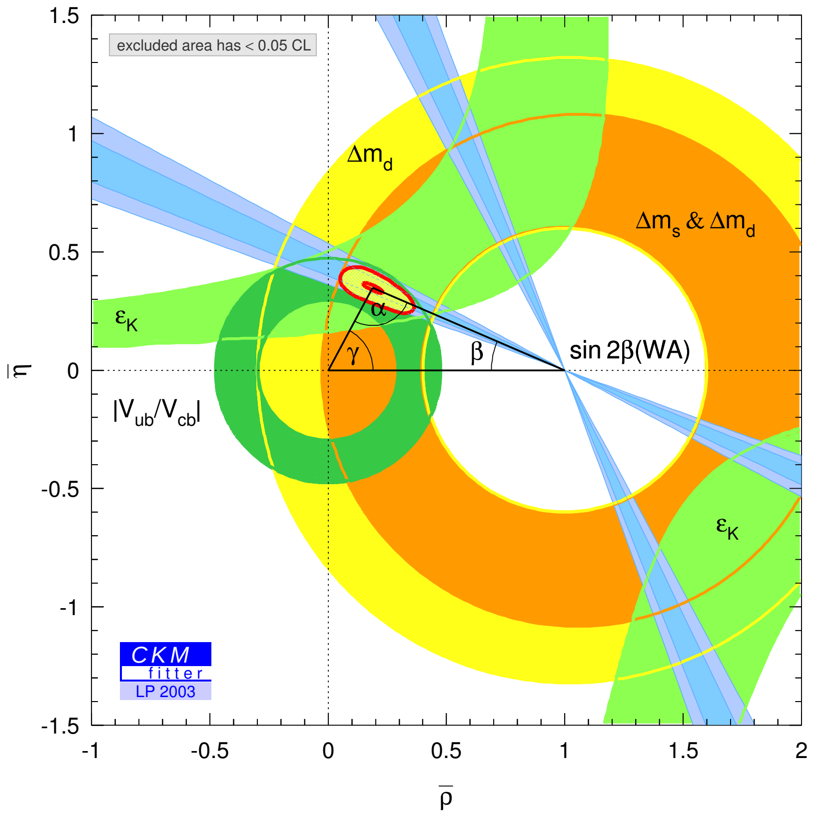
- Wolfenstein parameterization (1983) :
  $\lambda \equiv sin\theta_C = 0.22, \;\; A, \;\; \rho, \;\; \eta.$

- ρ and η are hard to measure,
  because they are in V_{ub} and V_{td} of $O(\lambda^3)$.
  $\rightarrow$ "rare" processes in K and B decays.

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

$$\underline{4.75 \times 10^{-11}} \quad \bullet \quad A^4 \cdot X(x_t)^2 \cdot [\ (\rho_0 - \rho)^2 \ + \ \eta^2\ ]$$

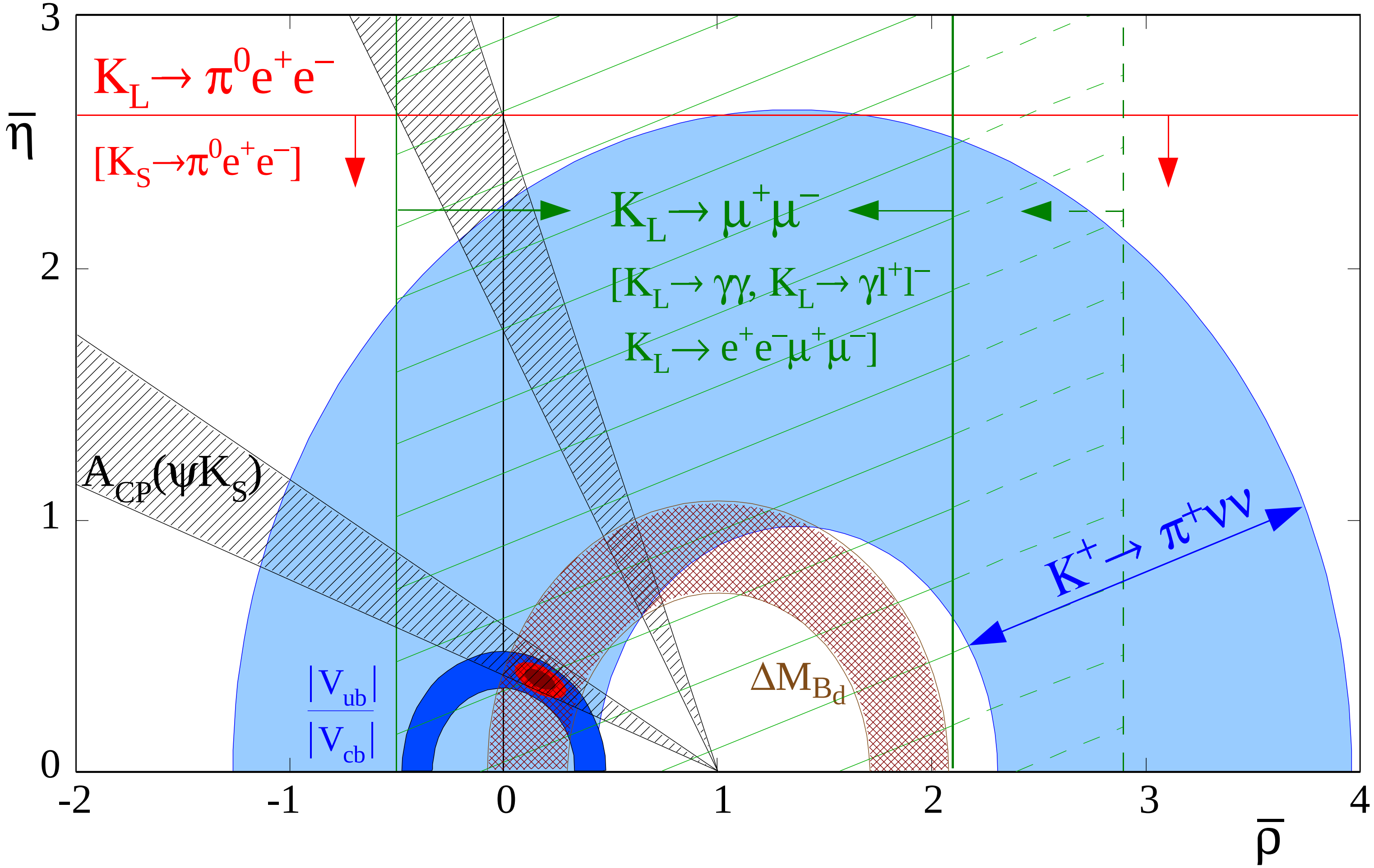




(ρ, η) constraints @LP03

	Isidori hep-ph/0307014	Buras et al hep-ph/0402112
$K^+ \to \pi^+ \nu \bar{\nu}$	$(7.7 \pm 1.1) \times 10^{-11}$	$(8.0 \pm 1.1) \times 10^{-11}$
$K_L^0 \to \pi^0 \nu \bar{\nu}$	$(2.6 \pm 0.5) \times 10^{-11}$	$(3.2 \pm 0.6) \times 10^{-11}$

$\Delta S = 1 \ (\rho, \eta)$ Isidori & Unterdorfer, hep-ph/0311084



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

- Minimal Flavor Violation   Buras, hep-ph/0310208

	SM	MFV
$K^+ \to \pi^+\nu\bar{\nu}$	$(7.7 \pm 1.1) \times 10^{-11}$	19.1×10^{-11}
$K_L^0 \to \pi^0\nu\bar{\nu}$	$(2.6 \pm 0.5) \times 10^{-11}$	9.9×10^{-11}

- $B \to \pi\pi$, $K\pi$ and New Physics

  Buras et al., PRL 92, 101804(2004), hep-ph/0402112

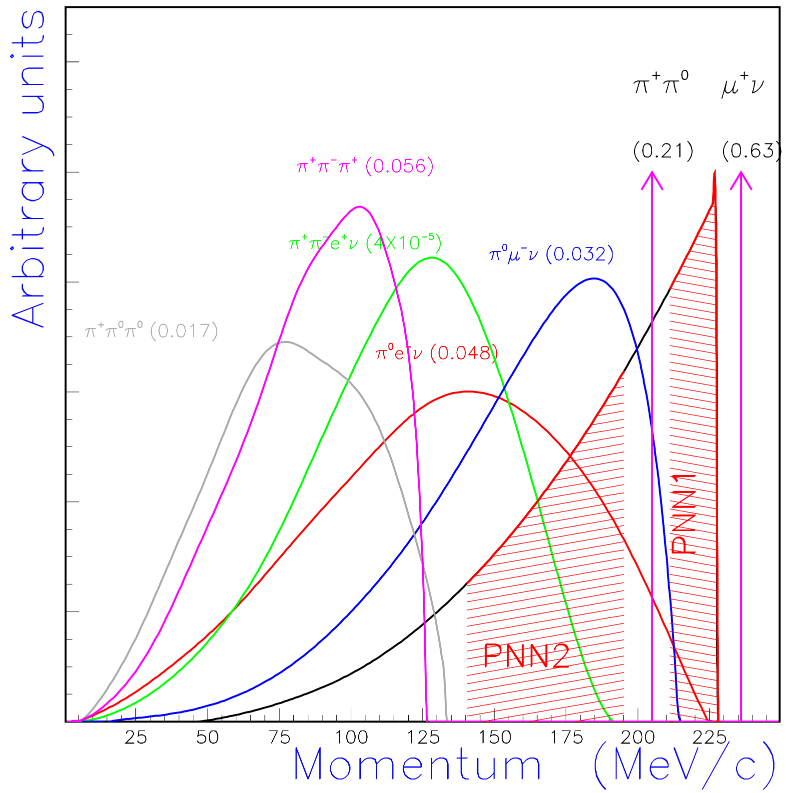
  S. Recksiegel, KEK Theory Seminar scheduled on April 13

	SM	NP
$K^+ \to \pi^+\nu\bar{\nu}$	$(7.7 \pm 1.1) \times 10^{-11}$	$(7.5 \pm 2.1) \times 10^{-11}$
$K_L^0 \to \pi^0\nu\bar{\nu}$	$(2.6 \pm 0.5) \times 10^{-11}$	$(3.1 \pm 1.0) \times 10^{-10}$

* $(sin2\Phi_1)_{B^0 \to \Phi K_S} \approx +0.9 \Leftarrow \underline{-0.96 \pm 0.50}$ by Belle

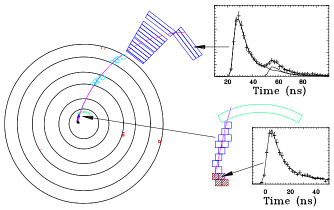
Name	**“PNN2”**	**“PNN1”**
P_π (MeV/c)	[140,195]	[211,229]
Years	1996-97	1995-98
Stopped K^+	1.7×10^{12}	5.9×10^{12}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

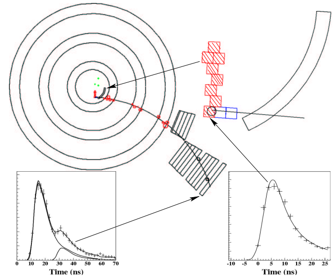
E787 $\mathbf{K^+ \to \pi^+\nu\bar{\nu}}$ results



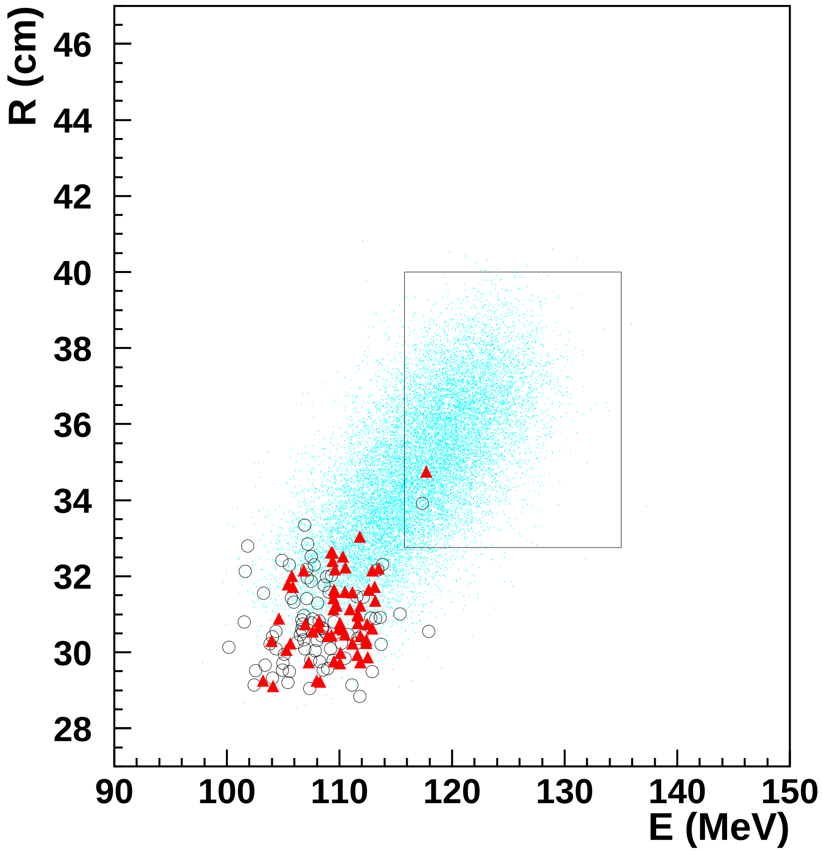
PNN1: PRL **88**, 041803 (2002).

PNN2: limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 (hep-ex/0403034) data.





E787-PNN1: PRL **88**, 041803 (2002)



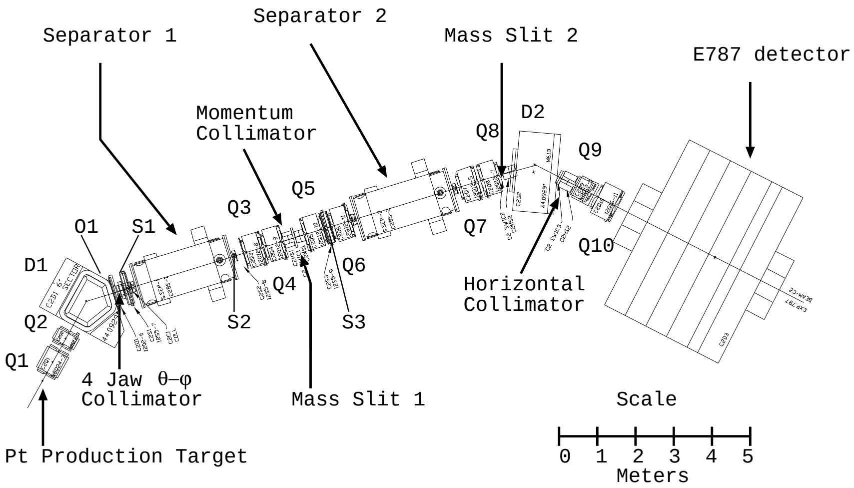
- π^+ Range vs Energy
- 95-97 / 98 / MonteCarlo

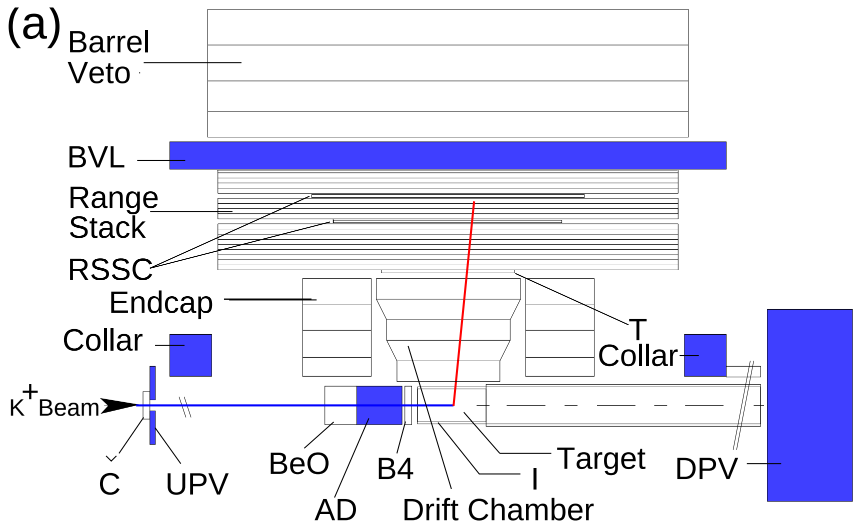
E949 experiment in 2002

BNL-AGS: $\geq 60 \times 10^{12}$(Tera) protons per spill

		E787-'98	E949-'02
protons per spill	Tp	25-40	70
AGS energy	GeV	24	22
beam spill	sec	2.2	2.2
cycle	sec	4.2	5.4
duty factor	%	52	41

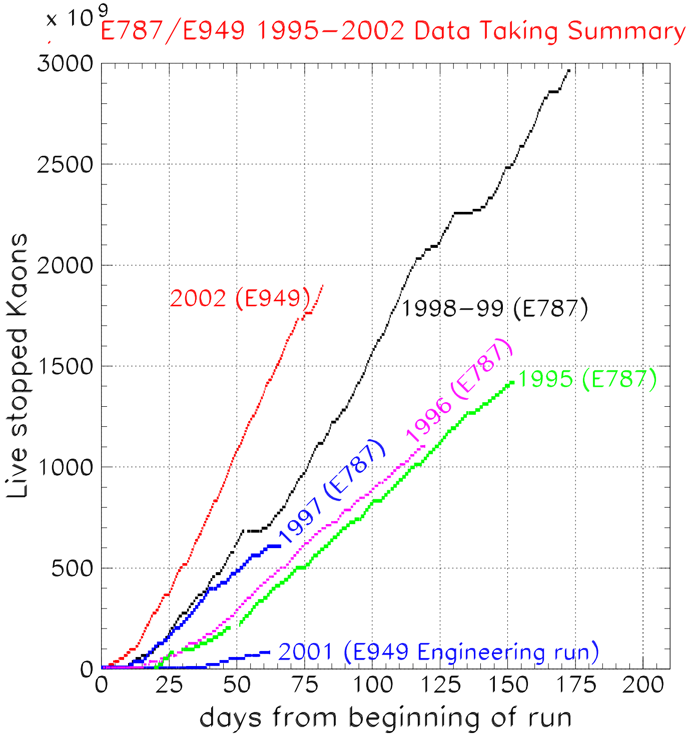
LESB3 → K^+ slowed by degrader and coming to rest





	E787-’98	E949-‘02
K^+/π^+	4	3
kaon momentum MeV/c	710	710
stopping fraction %	28	28

		E787	E949-'02
N_K in the spill	M	1.8	2.5
N_K	MHz	0.8	1.2
rates in the detector			$\times 2$
N_K accumulated		5.9×10^{12}	1.8×10^{12} $\times 0.305$



# of kaons incident on the target (N_K)

- 12 weeks (March-June 2004)

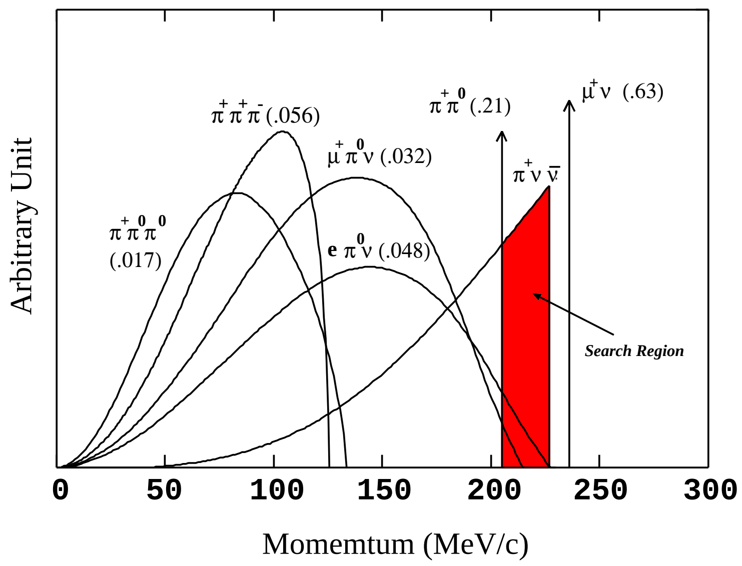
Reminder: E949-2002 beam conditions were not optimized

- a failure of the AGS power supply
- reduced operating voltage of one of the DC separators
- 12 weeks

The conditions will be improved in the next run.

		E787	E949-'02	E949 optimized
AGS energy	GeV	24	22	24
beam spill	sec	2.2	2.2	4.1
cycle	sec	4.2	5.4	6.4
duty factor	%	52	41	64
K^+/π^+		4	3	4
N_K in the spill	M	1.8	2.5	5.0
N_K	MHz	0.8	1.2	1.2
rates in the detector			$\times 2$	$\times 2$ or less
beam time	weeks		12	$\geq$60

K^+decay at rest $\rightarrow \pi^+ +$ "nothing"

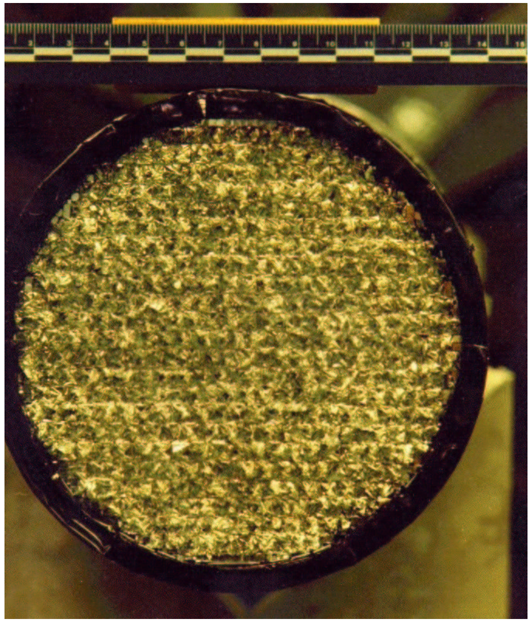


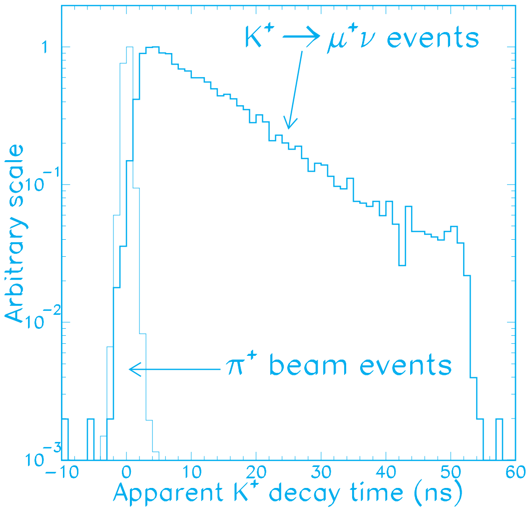
Background Rejection

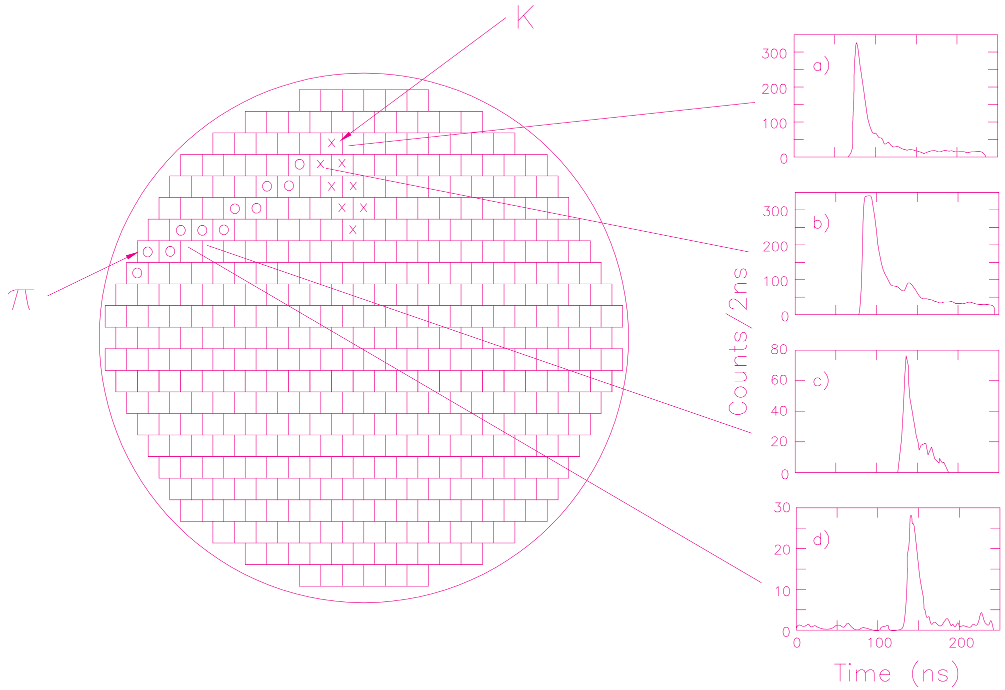
- Kinematics of π^+
  - Momentum
  - Kinetic Energy
  - "Range" in plastic scintillators
- π^+/μ^+ separation
  $\Longleftrightarrow K^+ \rightarrow \mu^+\nu$
- extra particles (γ, ..)
  $\Longleftrightarrow K^+ \rightarrow \pi^+\pi^0$

each weapon should have rejection of $\underline{10^6 \sim 10^7}$

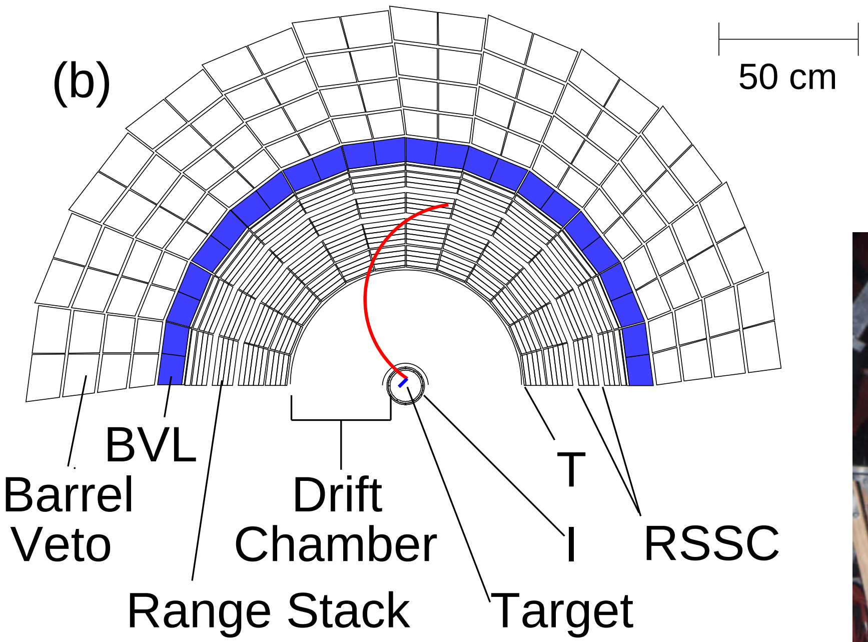
K^+ decay at rest in the Target (end-view)

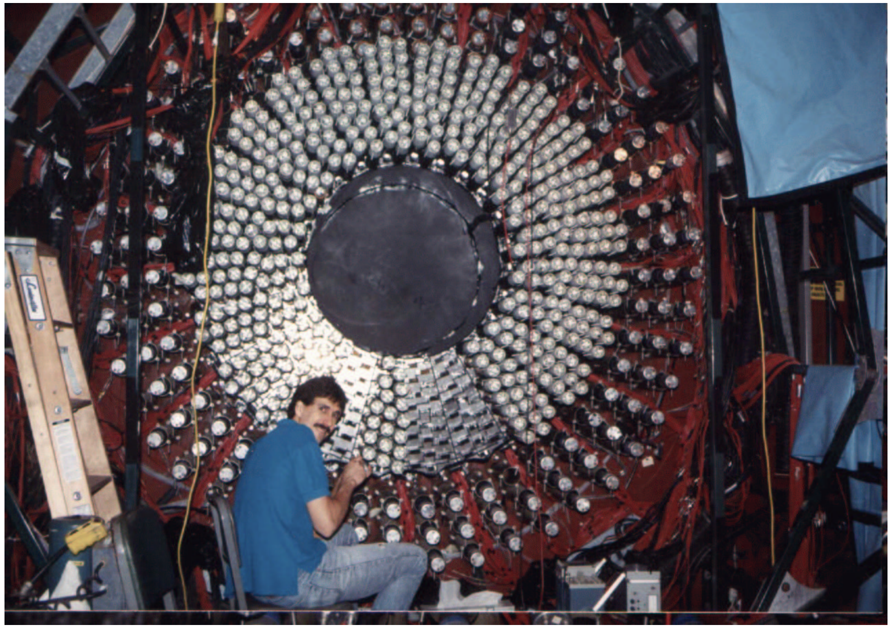




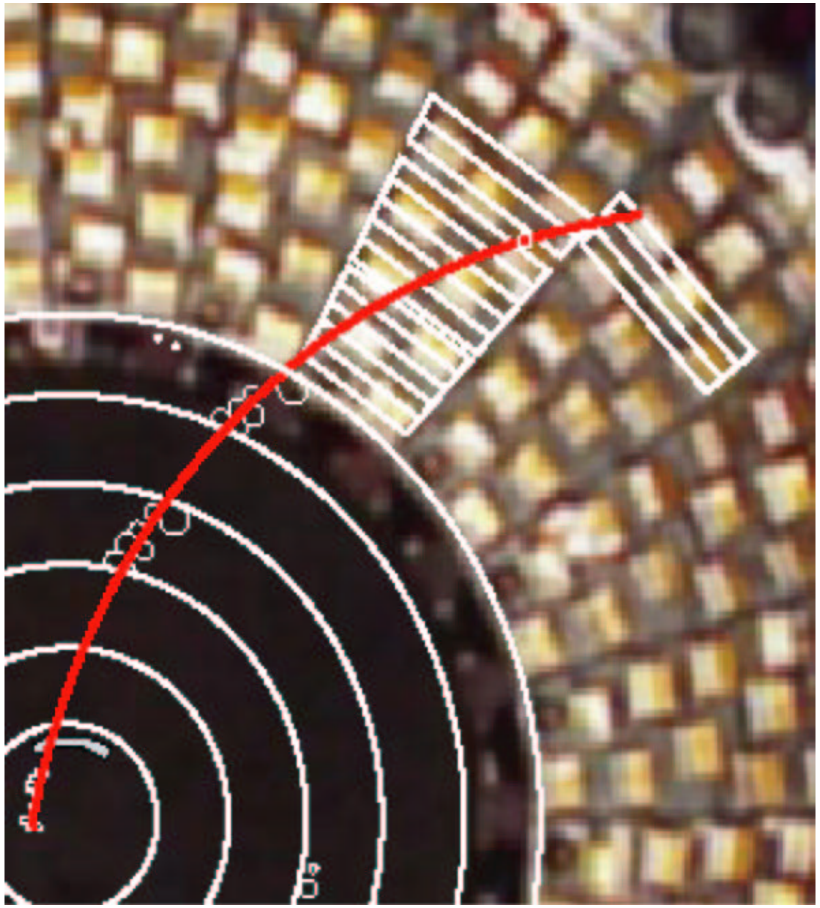


Charged track from the Target to the Range Stack

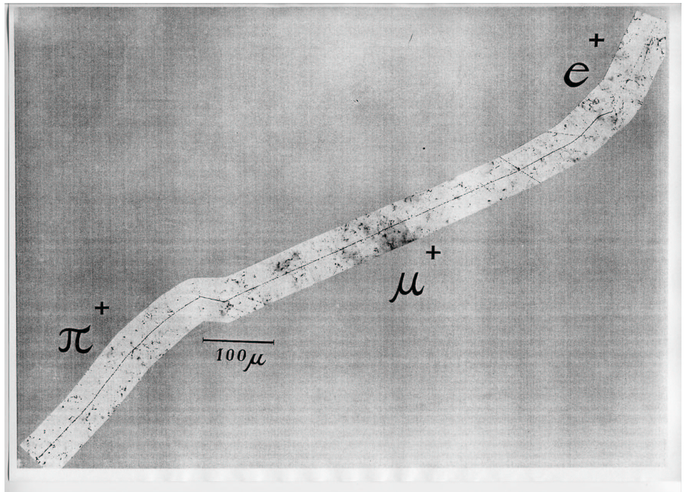




π^+ loses energy and comes to rest in the RS



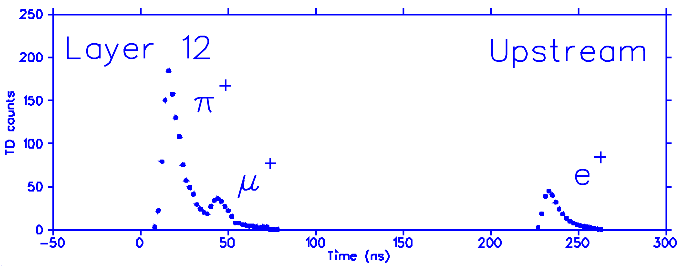
in the stopping counter ...



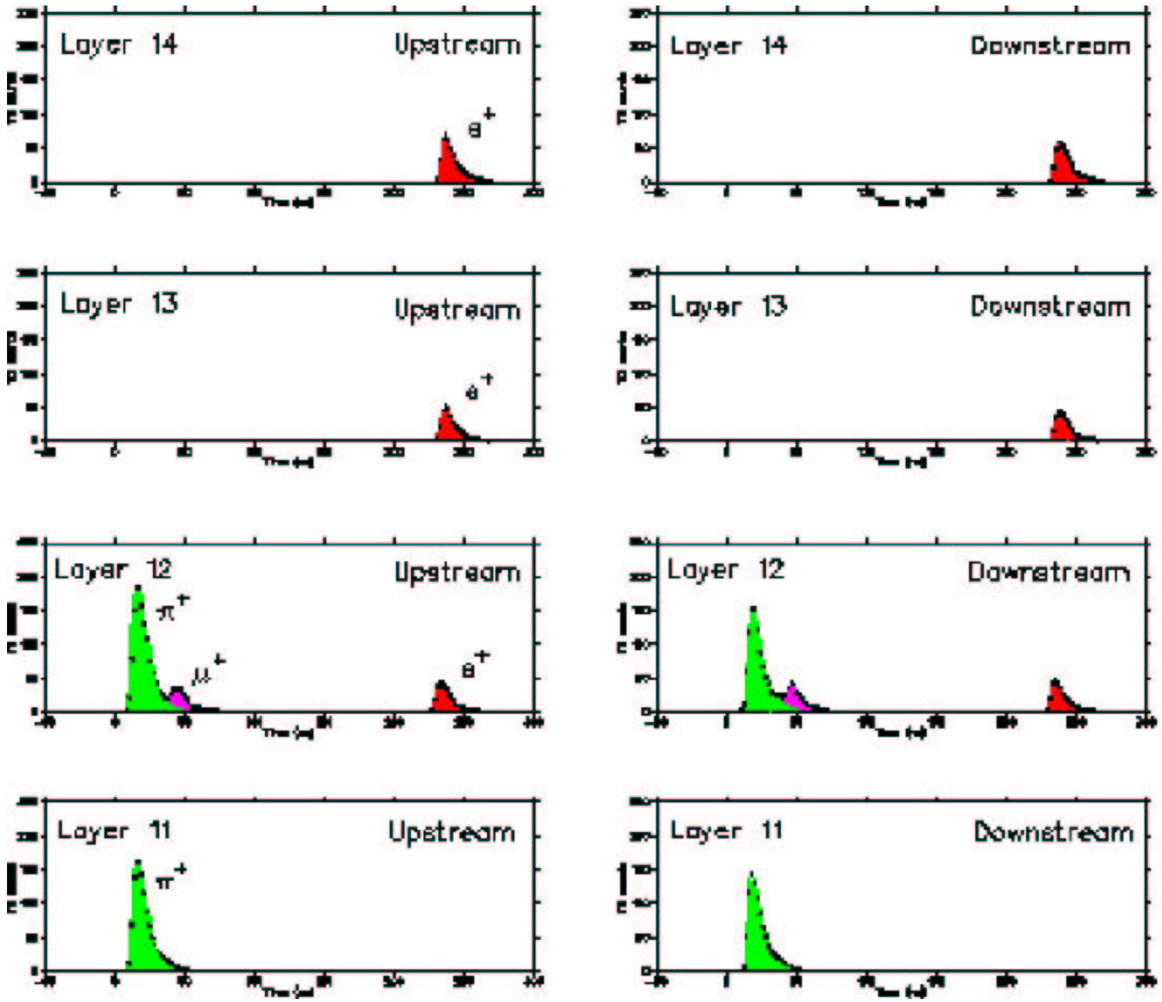
first π^+ and its decay by Japanese accelerator (1962) in Nuclear Emulsion;

to the memory of INS-Tokyo (–1997 March).

from the plastic scintillator to PMT



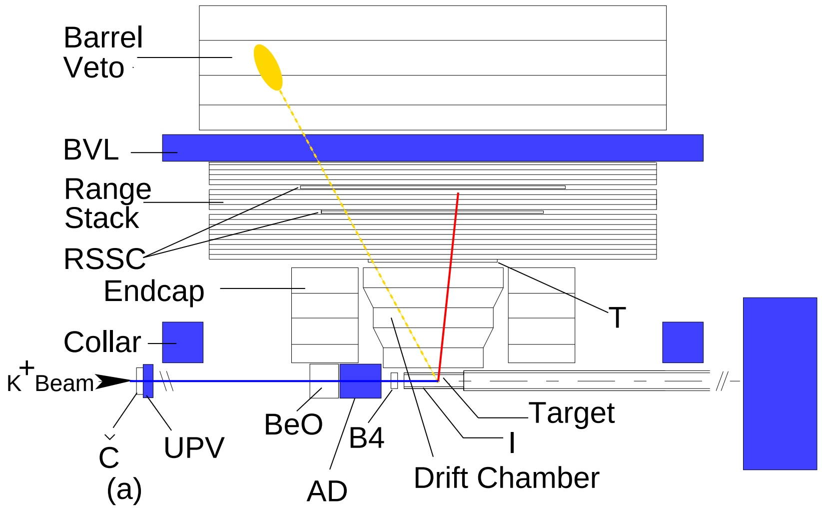
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ recorded by 500-MHz waveform digitizer



Online + Offline μ^+ rejection ($> \ 10^5$)

γ detection by the hermetic Calorimetry $\Rightarrow$ "Photon Veto"

with Barrel Veto, Endcap, Range Stack, Target

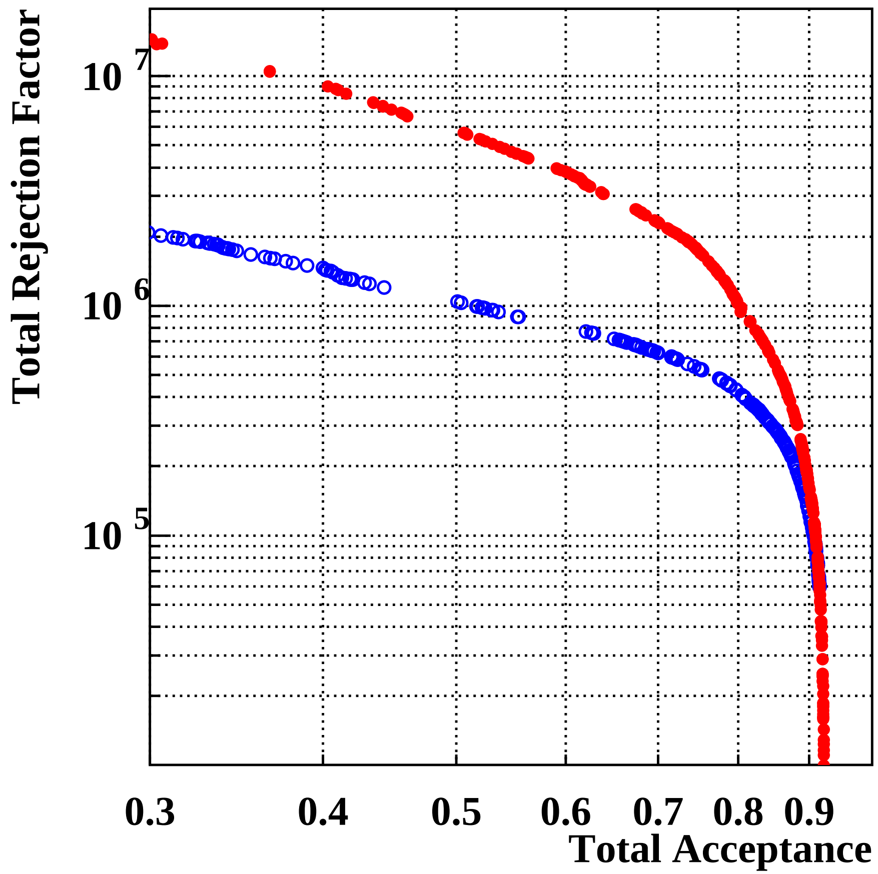


new Calorimeters:

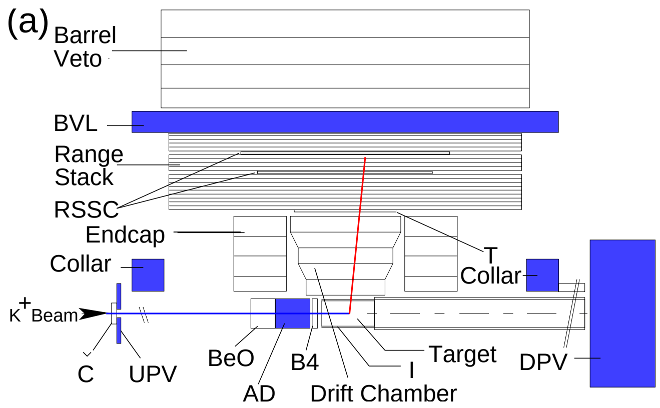
- barrel part:
  - Barrel Veto Liner (BVL)
    add 2.3 X_0
- minor openings
  along the beam direction
  - segmented Active Degrader
  - new Collar detectors
  - Upstream, Downstream PV

E949 improvements (1): "Photon Veto"

- PV cuts:
  $\frac{\pi^0 \text{ Rejection}}{\pi^+\nu\bar{\nu} \text{ Acceptance}}$ as a function of
  for E949 and E787.
- $\times 2$ better rejection
  at nominal acceptance (80%)



E949 upgrades (2): Rate capability, Kinematics

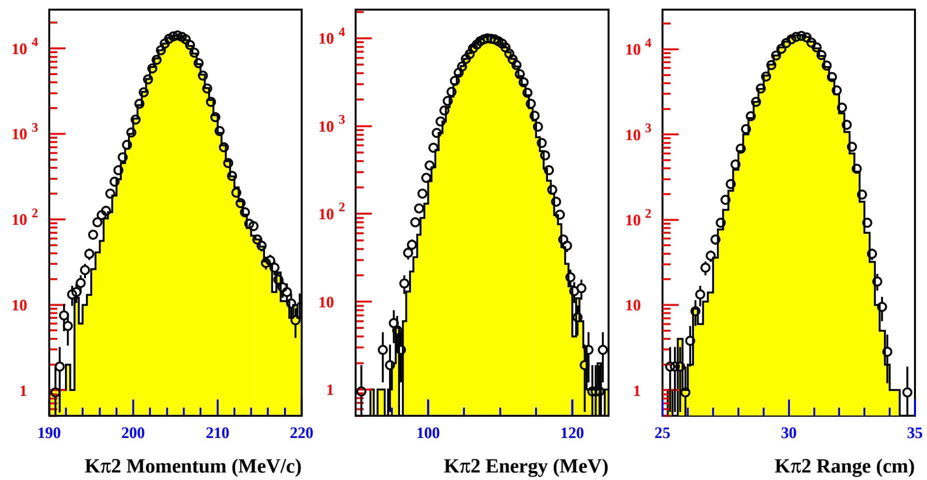


- higher segmented B4 hodoscope
- record waveforms from beam counters
- RS Layer 1-5, 19 replaced
  $\longrightarrow$ more light output
- LED flasher system $\longrightarrow$ RS monitor
- new wire-chamber electronics

π^+ kinematics from $K_{\pi 2}$:
E787($\circ$) vs E949 (histo)

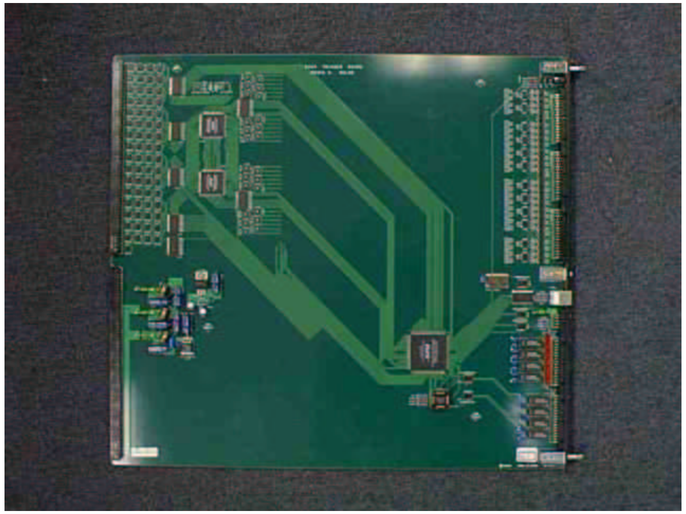
- $\sigma_P = 2.3$ MeV$/c$
- $\sigma_E = 3.0$ MeV
- $\sigma_R = 0.9$ cm

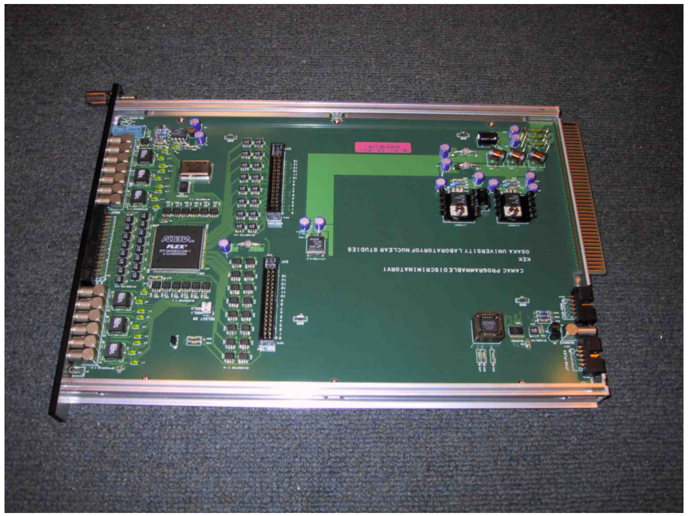
Reminder:
the rate is $\times 2$ higher in E949.

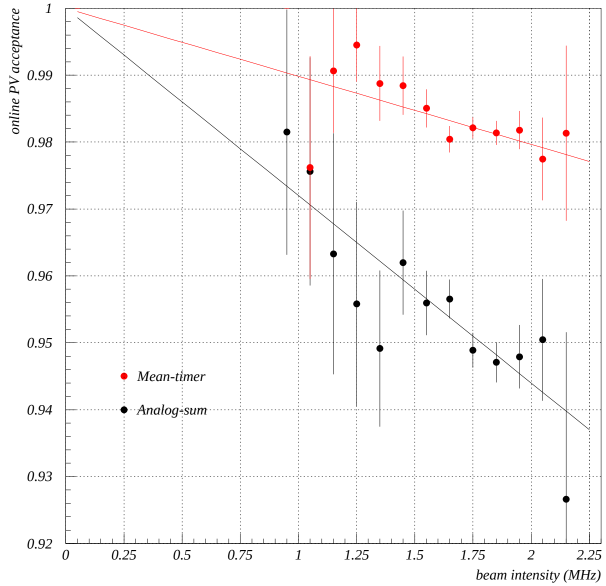


E949 upgrades (3): Trigger/DAQ

e.g. Level0 trigger board and digital Meantimer module







T.Yoshioka, M.Nomachi et al., KEK Preprint 2003-109, IEEE TNS (in press)

Analysis

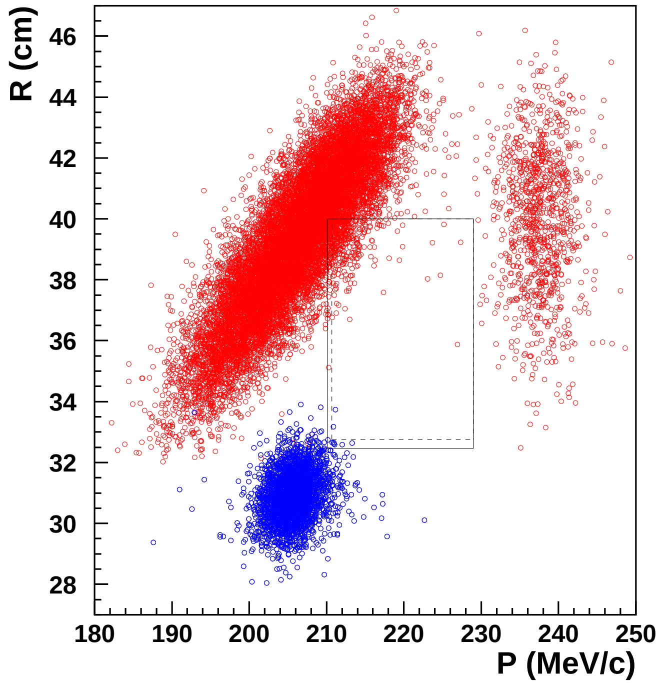
Search region ("BOX") in the multi-dimesional "cut" space

"cuts" $\equiv$ Selection Criteria

1. π^+ kinematic-region cuts:
   - Momentum above $K_{\pi 2}$: 211<P<229 MeV/c
   - Range(R), Kinetic Energy (E)
   - Range-Momentum relation
2. Event Identification ("Rejection" cuts)
   - Photon Veto
   - $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain
3. Beam cuts: K^+ decay at rest, no extra beam particles, ..
4. "Pathology" cuts
   - failures in the reconstuction of pattern/energy/timing
   - ...

characterizing the background sources

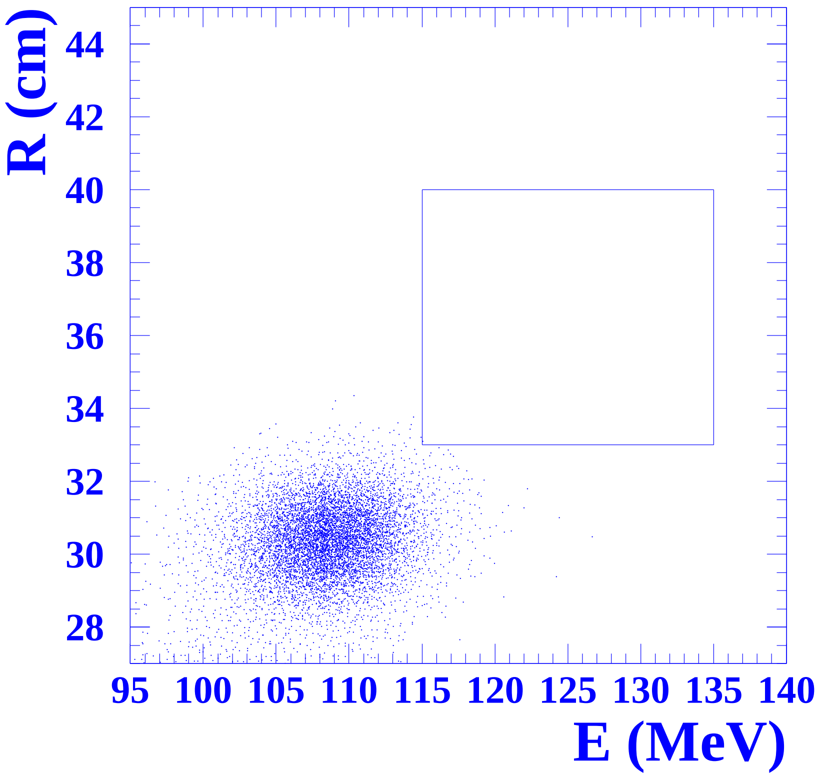
- $\mathrm{K}_{\pi 2}$: $K^+ \rightarrow \pi^+\pi^0$
  - proximity (P,E,R) to $\mathrm{K}_{\pi 2}$ peak: `Kp2-K`
  - Photon veto timing-windows/energy-thresholds: `PV`
- $\mathrm{K}_{\mu 2}$: $K^+ \rightarrow \mu^+\nu$ but R is small due to interactions in the RS
  - proximity (P) to $\mathrm{K}_{\mu 2}$ tail: `Km2t-K`
  - $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ properties via Neural Network func: `TD`
- $\mathrm{K}_{\mu m}$: multi-body decays ($K^+ \rightarrow \mu^+\nu\gamma$,$K^+ \rightarrow \mu^+\pi^0\nu$, ..)
  - proximity (R,P) to the $\mathrm{K}_{\mu\ 2}$ band: `Km2b-K`
  - `TD`

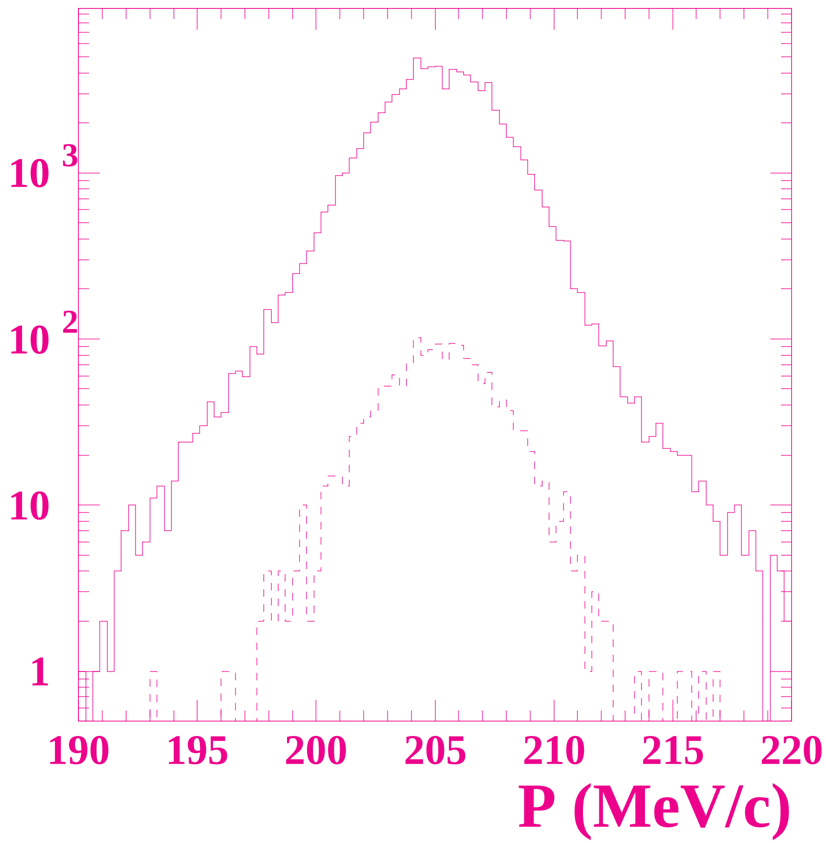


Background studies: our policy and philosophy

- To avoid bias due to small statistics,
  - 1/3 of sample: for study
  - 2/3 of sample: (keep untouched)
- **invert** at least one of the cuts to:
  - enhance the backgrounds collected by the trigger
  - prevent candidate events from being examined ("Blind Analysis" even at the event selection)
- Cuts were **frozen** with the 1/3 sample.
- Then measure the background levels in the search region with the remaining (independent) 2/3 sample.

Example: $K^+ \rightarrow \pi^+\pi^0$ background study with "two cuts"





Normalization for Kp2:

- select events with photons,
- measure proximity of (P,E,R) to $K_{\pi 2}$ peak

Rejection for PV:

- select events whose (P,R,E) are in $K_{\pi 2}$ peak,
- measure rejection by Photon Veto

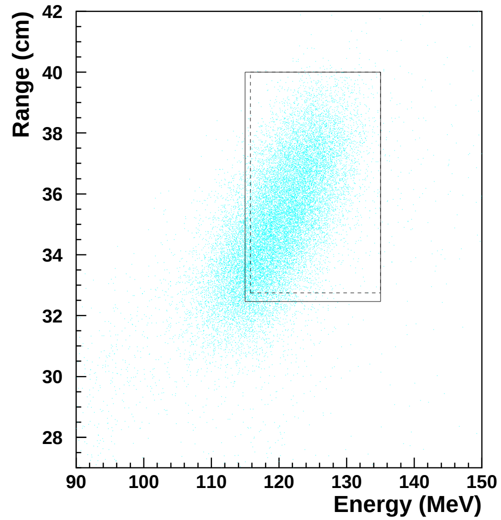
Background levels in the Search region

- $K_{\pi 2}$ background level got larger (see the next slide).

Source	E787	E949-'02
$K_{\pi 2}$	0.032	0.216 ± 0.023
Muon	0.064	
$K_{\mu 2}$		0.044 ± 0.005
$K_{\mu m}$		0.024 ± 0.010
Beam (single+double)	0.024	0.009 ± 0.003
K^+ charge exchange	0.026	0.005 ± 0.001
Total background	0.14 ± 0.05	0.298 ± 0.026

Acceptance and Sensitivity in the Search region

- In E949, we loosened
  - Kp2-K: lower edge of (P,E,R) to seek better acceptance
  - PV and TD (improved in E949) to keep acceptance in $\times 2$ higher rates.



		E787	E949-'02
N_K		5.9×10^{12}	1.8×10^{12} $\times 0.305$
Total background	events	0.14 ± 0.05	0.30 ± 0.03
Total acceptance	%	0.20 ± 0.02	0.22 ± 0.02 $\times 1.1$
Single Event Sensitivity		0.83×10^{-10}	2.6×10^{-10} $\times 0.336$

We are ready to open the "BOX"

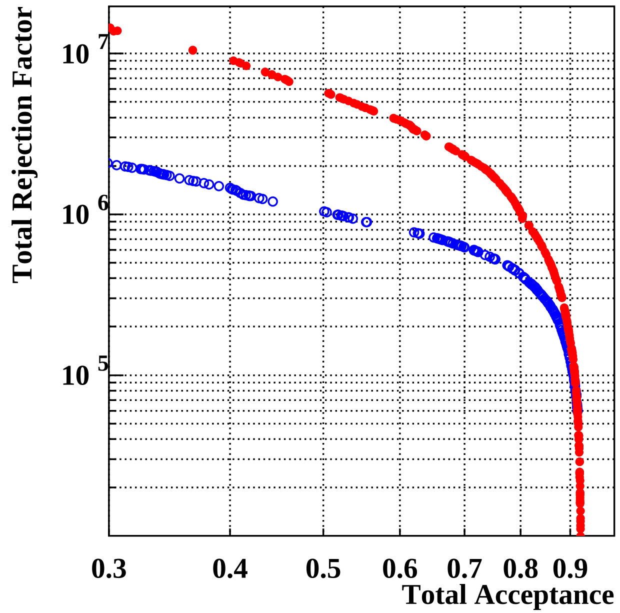
if we would perform
a simple "counting" experiment

(# of candidate events vs. background level)

Isn't the total background (0.30 ± 0.3) a little bit high ?
Did you get into a <u>background-limited</u> situation ??

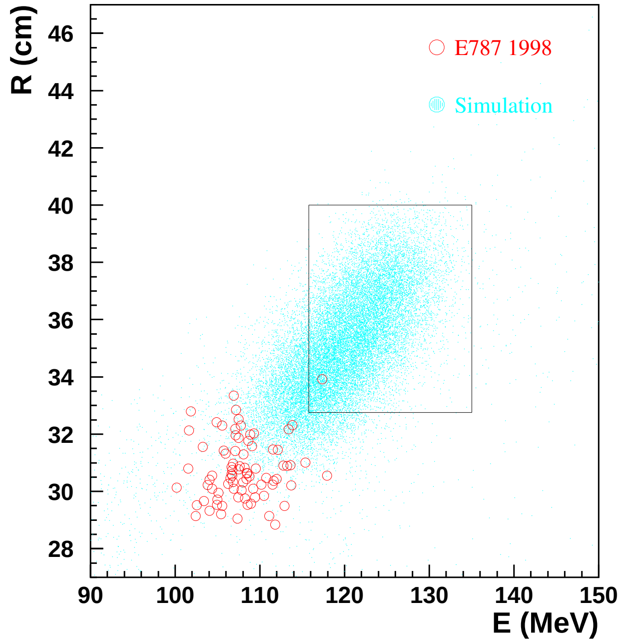
Rare Kaon-decay searches (sensitivity $\leq 10^{-10}$)

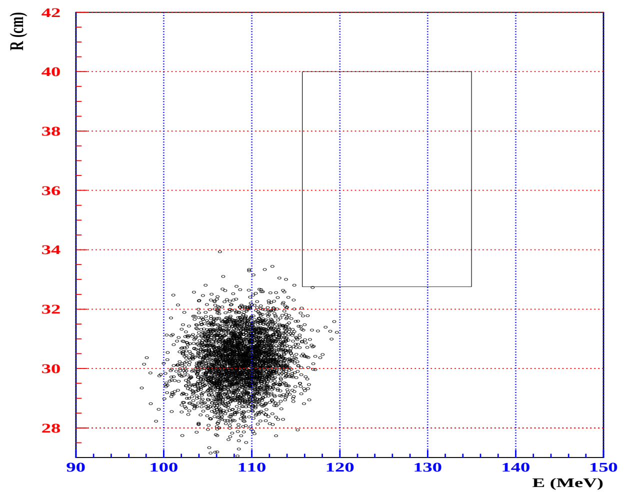
- Bgd levels (< 1 event),
  expected # of events (0 or 1 or 2 ...):
  both in small statistics
  - a dedicated experiment
    to a specific decay mode
    with a special-purpose detector
  - not easy to increase the acceptance



- We understand the behavior of background sources
  (where they appear in the "cut" space).

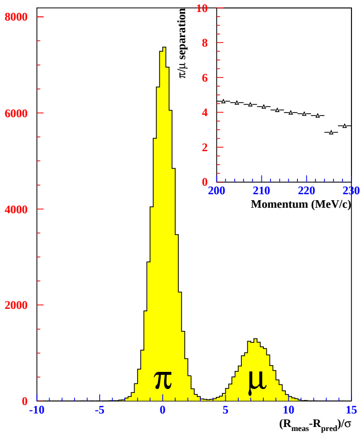
$K_{\pi 2}$ kinematic Bgd shape (plots from E787-98)

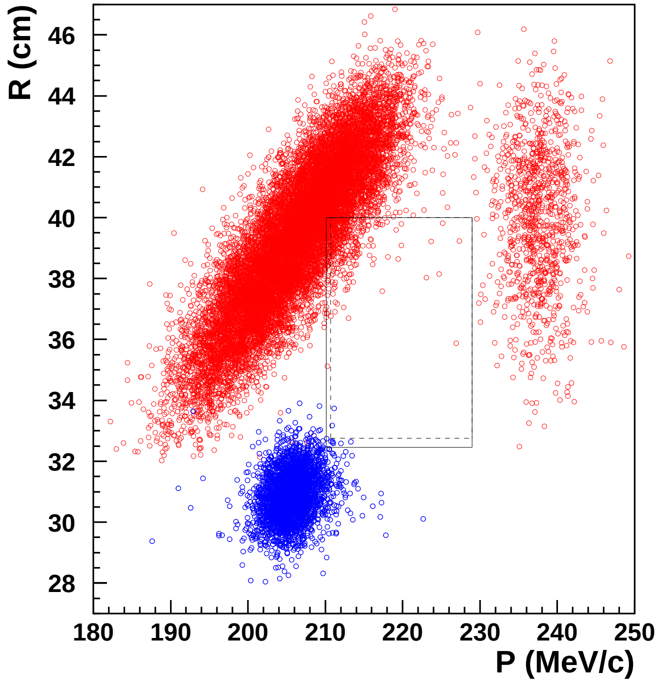


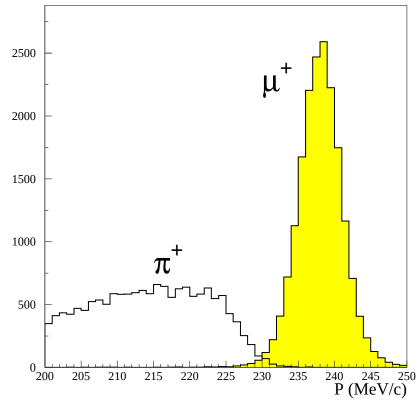


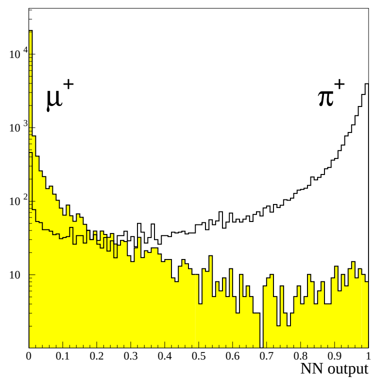
- sub-divide inside and just-outside the "BOX" into many small "cells"
  - proximity of (P,E,R) to the $K_{\pi 2}$ peak:
    $(P,E,R) \geq (P_B,E_B,R_B) \pm \underline{n \times 5\% \times (\sigma_P,\sigma_E,\sigma_R)}$
- evaluate Acceptance A_i and Background level b_i for each cell (labeled by $\boxed{i}$)

Muon Bgd shape: $K_{\mu m}$(band) and $K_{\mu 2}$(tail)









TD cut using Neural Network

- for each cell (labeled by i),
  - Acceptance A_i and BR (as a free parameter)

    $\Longrightarrow$ expected Signal $\boxed{S_i(BR)} \equiv BR \bullet \mathrm{N}_K \bullet A_i$
  - Background level $\boxed{b_i}$
- after opening the BOX, count:
  - $\#$ of observed candidates in each bin $\boxed{d_i}$
- Assume both $S_i(BR)$ and b_i are small

  $\longrightarrow$ use of Poisson statistics

  for "likelihood ratio" (signal-like outcomes vs. background-like ones)

$$X_i(BR) \equiv \frac{\exp^{-(S_i+b_i)}(S_i + b_i)^{d_i}}{d_i!} \Big/ \frac{\exp^{-b_i}(b_i)^{d_i}}{d_i!} = \exp^{-S_i}(1+\frac{S_i}{b_i})^{d_i}$$

Likelihood estimator: $X(BR) = \prod_{i=1}^{n} X_i$

T. Junk, NIM A434(1999), 435

$$X(BR) = \prod_{i=1}^{n} \frac{\exp^{-(S_i+b_i)}(S_i+b_i)^{d_i}}{d_i!} \Big/ \frac{\exp^{-b_i}(b_i)^{d_i}}{d_i!} = \prod_{i=1}^{n} \exp^{-S_i}(1+\frac{S_i}{b_i})^{d_i}$$

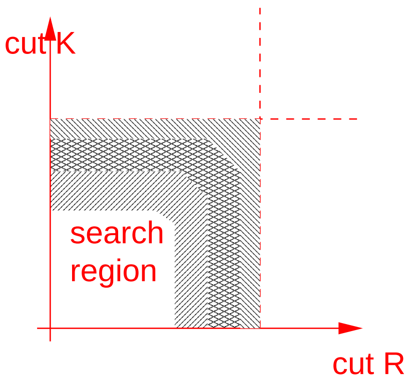
1. provide Junk's computer-program with
   - a set of ($\boxed{S_i(BR)}$, $\boxed{b_i}$, $\boxed{d_i}$) based on an BR assumption
2. the program calculates the C.L. of the BR assumption from modified Frequentist's approach
   - $\boxed{f_i} \equiv S_i/b_i$: Signal-to-Background function
   - $\boxed{W_i} \equiv S_i/(S_i+b_i)$: effective "weight" or each to the BR
3. loop over possible BR's and get limits on BR with the C.L. you want.
4. BR which gives the maximum value of $X(BR)$: the central value

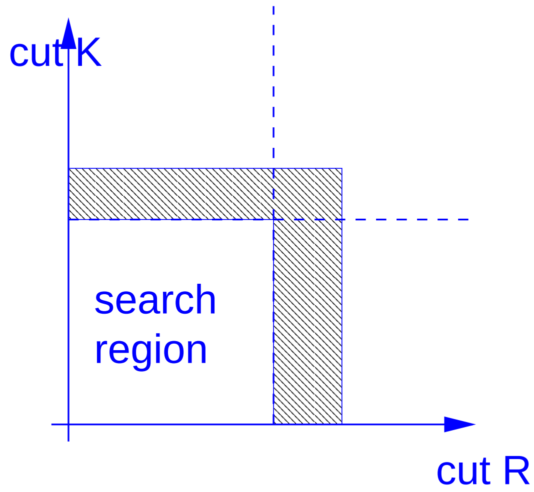
We are ready to open the "BOX".

We are not background-limited;

we perform
Likelihood analysis
to the candidate events
in the Search region.

Final check: "just-outside" the BOX region

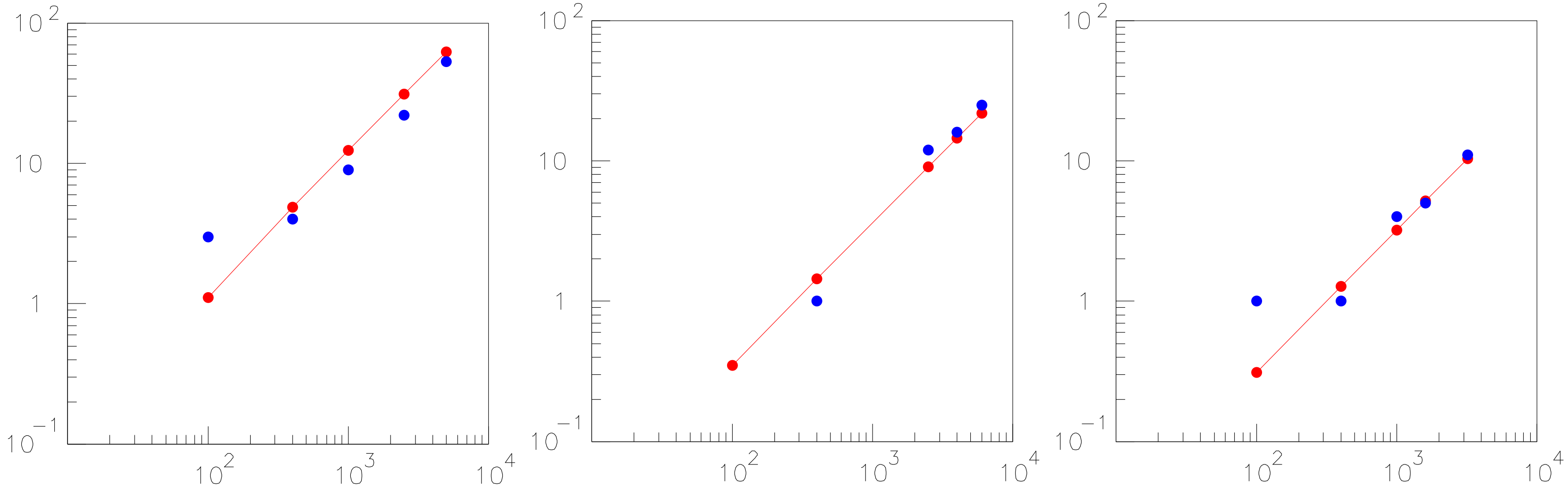




- Background levels b_i inside the BOX were evaluated, assuming that the kinematic-region cuts (cutK) and Rejection cuts (cutR) are independent.
- Let us confirm the assumption with the regions near the BOX: loosen, simultaneously,
  - cutK to reduce rejection by $\times N$
  - cutR to reduce rejection by $\times M$

  and we should observe $N \times M$ times more background events in the region.

	PV×KIN	10 × 10	20 × 20	20 × 50	50 × 50	50 × 100
$K_{\pi 2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD×KIN	10 × 10	20 × 20	50 × 50	80 × 50	120 × 50
$K_{\mu 2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	10 × 10	20 × 20	50 × 20	80 × 20	80 × 40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4



$K_{\pi 2}$: PV × KIN $K_{\mu 2}$: TD × KIN $K_{\mu m}$: TD × KIN

Results

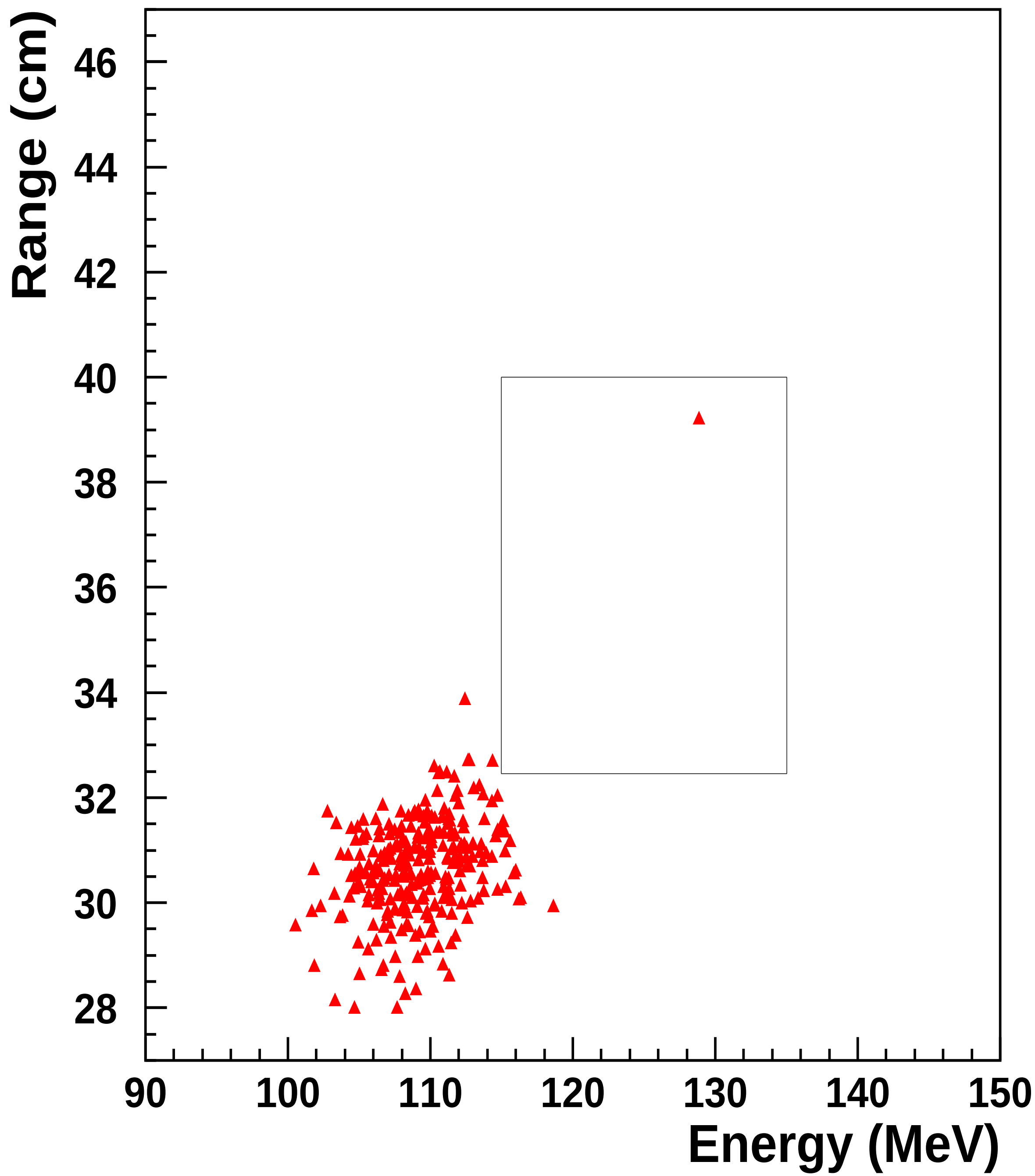
Opening the box

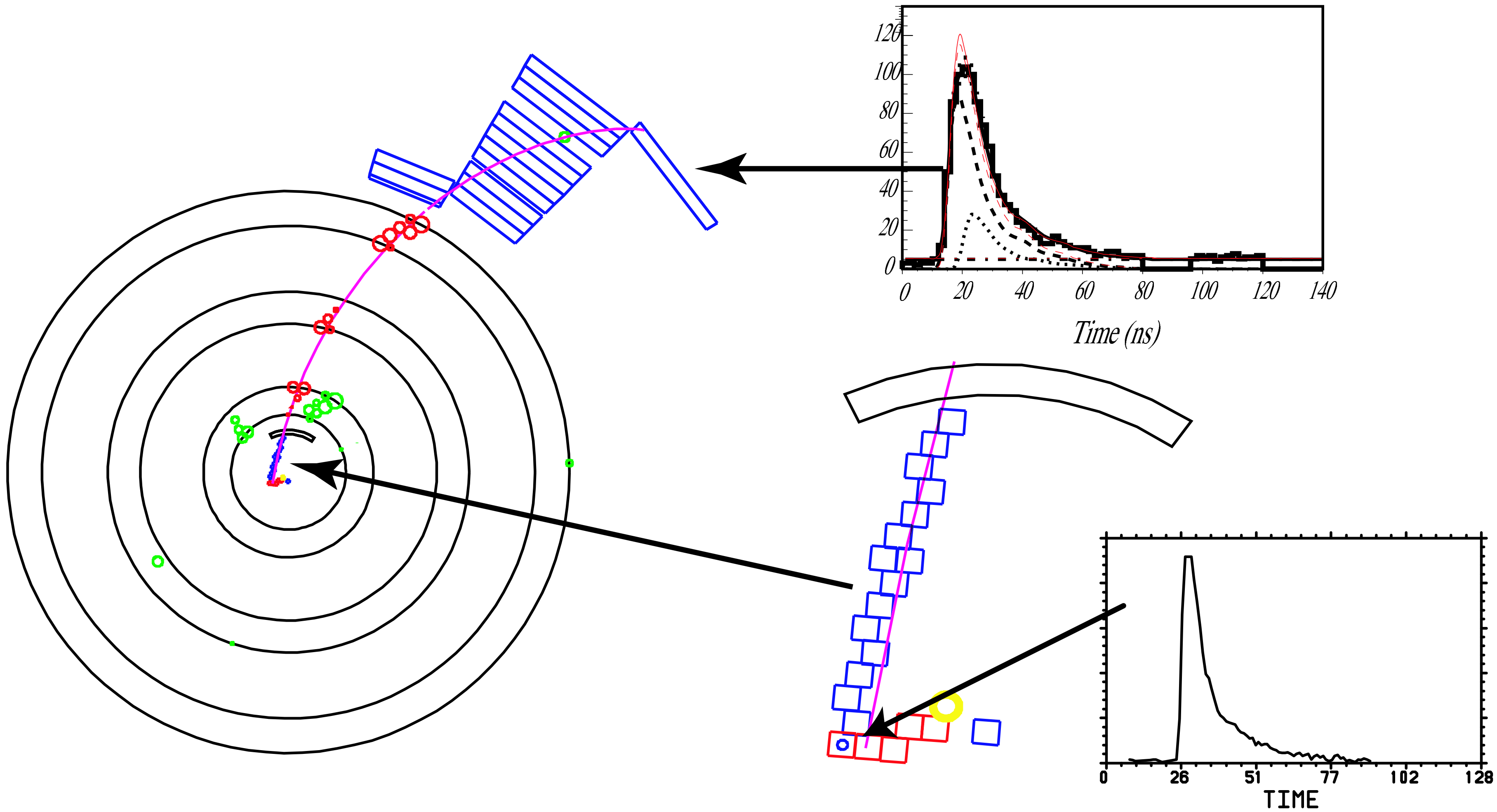
Range (cm) *vs* Energy (MeV)
for E949 data
after all other cuts imposed.

Solid line: Search region.

Single candidate found.

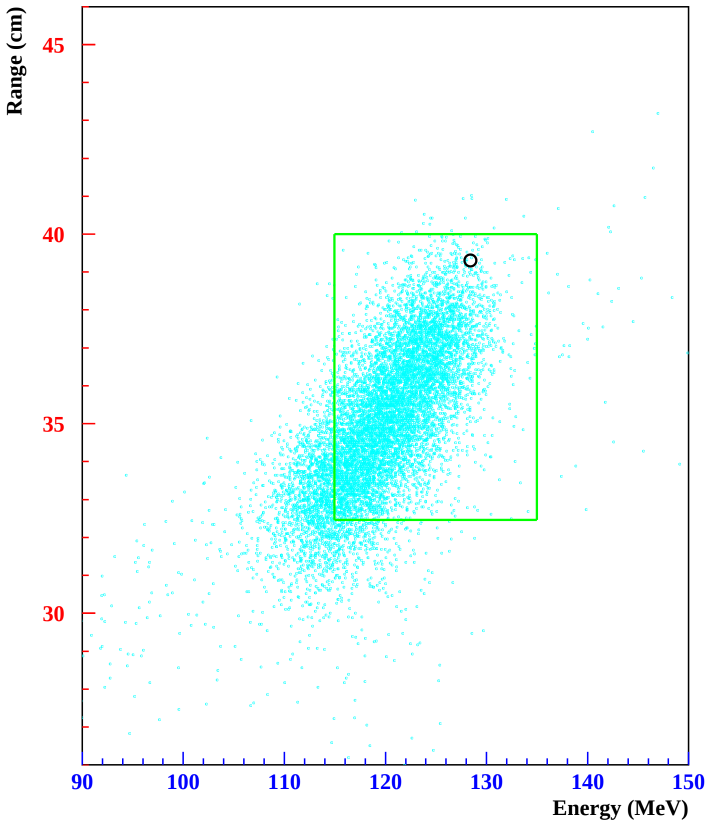
Cluster near 110 MeV:
unvetoed $K^+ \to \pi^+\pi^0$.



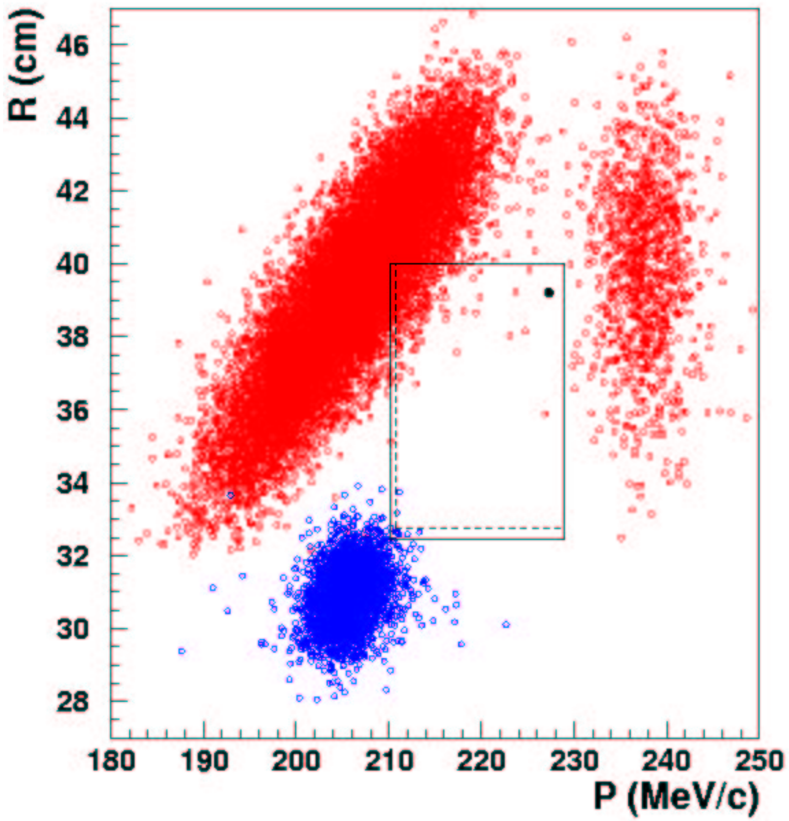

0
20
40
60
80
100
120
0
20
40
60
80
100
120
140
Time (ns)
0
26
51
77
102
128
TIME

quantities of the 3 events named as:		1995 E787A	1998 E787C	2002 E949A
P	(MeV/c)	218.2	214.0	227.3
R	(cm)	34.7	33.9	39.2
E	(MeV)	117.7	117.4	128.9
Photon		◯	◯	◯
$K^+ \to \pi^+$ decay time	(ns)	23.9	4.2	4.3
$\pi^+ \to \mu^+$ decay time	(ns)	26.9	16.5	6.2
$\mu^+ \to e^+$ decay time	(ns)	3253.	5333.	1370.
Beam		◯	◯	◯

Signal S_i



Background b_i



$$S_i(BR) = 2.8 \times 10^{-5}$$

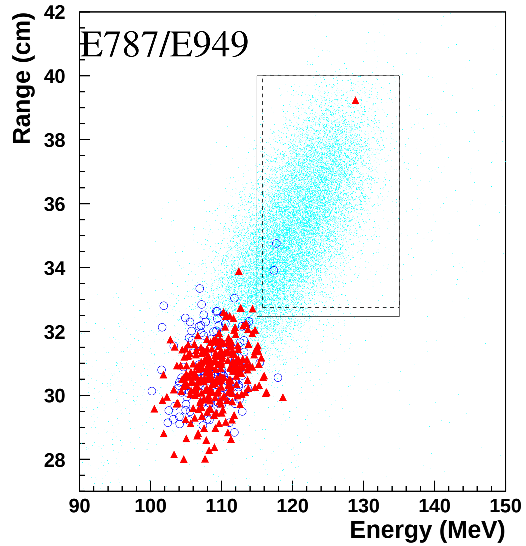
$$b_i \ = \ 5.7 \times 10^{-5} \text{ events}$$

with B.R.$_{SM}$=7.7×10^{-11}

B.R. with T. Junk method

E949 alone: $(0.96\ \ +4.09\ \ -0.47)\times 10^{-10}$

$\Rightarrow$ combine E787 and E949 data



	E787		E949
N_K	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate with $S_i(BR)/b_i$	1995A	1998C	2002A

$$\mathbf{B.R.(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}}\ \text{(68\%CL interval)}$$

	E787		E949
Candidate	1995A	1998C	2002A
S_i/b_i	50	7	0.9
W_i	0.98	0.88	0.48
Background Prob.	0.006	0.02	0.07

- B.R.$(\mathbf{K^+ \to \pi^+ \nu\bar{\nu}}) > \mathbf{0.42 \times 10^{-10}}$ at 90%CL:

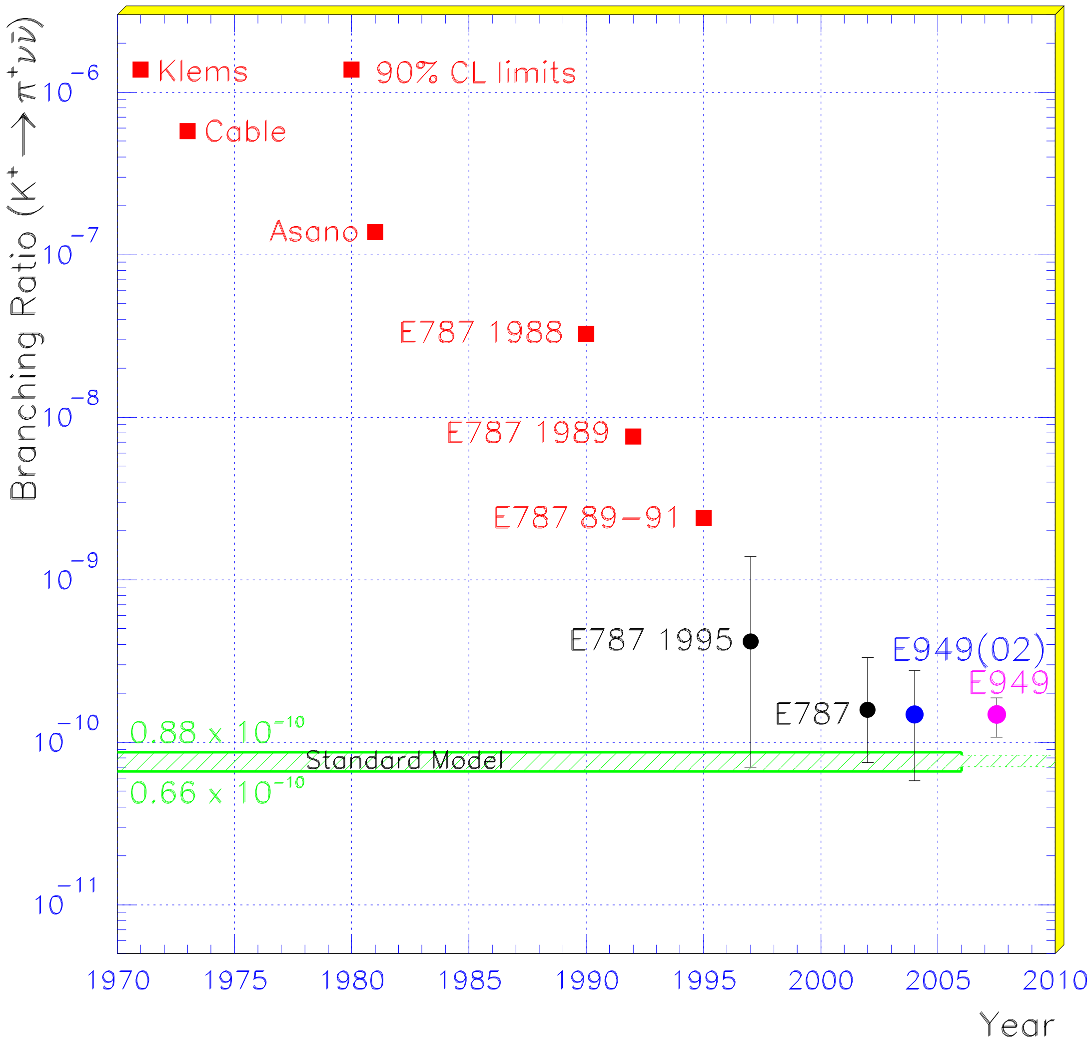
  the probability [a] that background alone gave rise to the three candidates or more:

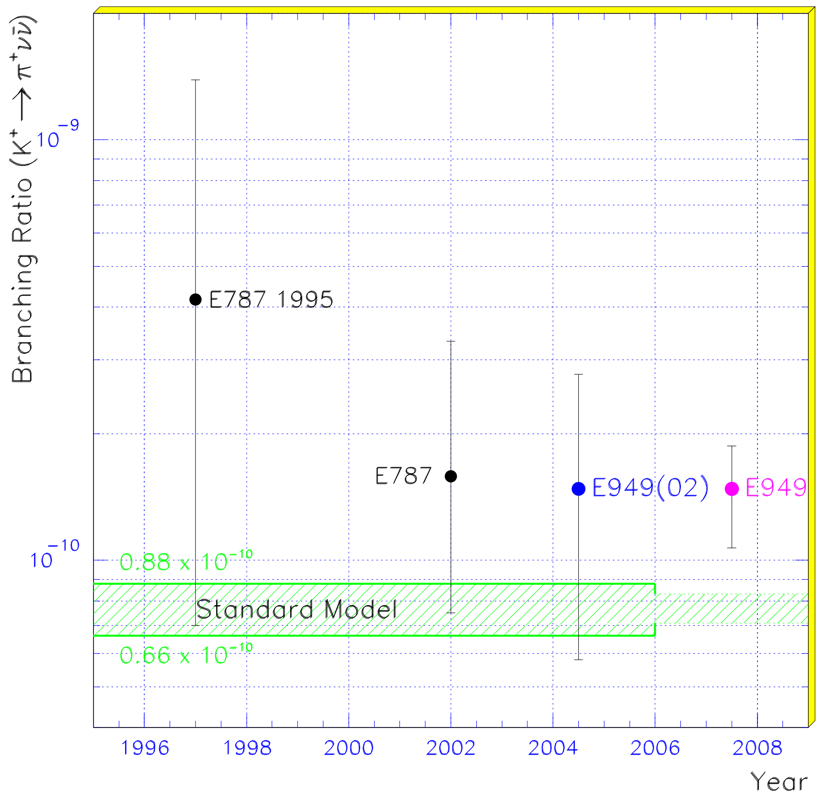
  0.001 ("$\mathbf{3\sigma}$" above the background).

- B.R.$(\mathbf{K^+ \to \pi^+ \nu\bar{\nu}}) < \mathbf{3.22 \times 10^{-10}}$ at 90%CL:
  $\Rightarrow$ Upper limit on B.R.$(\boldsymbol{K_L^0 \to \pi^0 \nu\bar{\nu}})$ by Grossman-Nir(1997): $\mathbf{1.4 \times 10^{-9}}$

- B.R.$(\mathbf{K^+ \to \pi^+ \nu\bar{\nu}})$ in the SM: $\mathbf{(0.77 \pm 0.11) \times 10^{-10}}$

[a] I am a Frequentist, not a Bayesian.





Narrowing of "SM prediction" assumes measurement of B_s mixing (at Tevatron, LHC, ..) consistent with prediction.

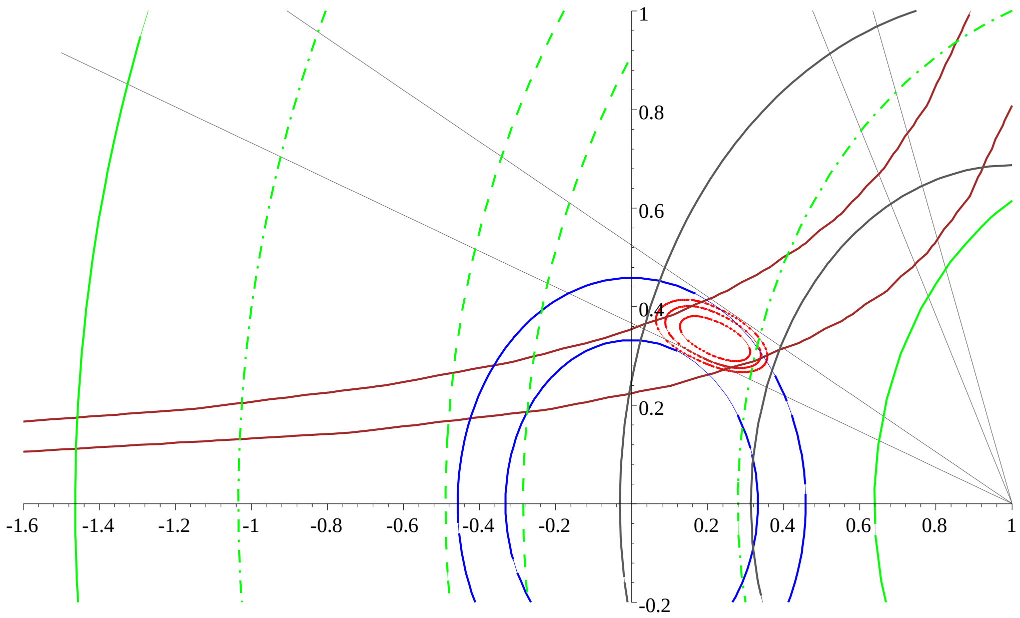
E949(02) = combined E787& E949.

E949 projection with full running period.

Impact of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ on Unitarity Triangle

by courtesy of G. Isidori

central value [dashed], 68% interval [dot-dash], 90% interval [solid]
(including theoretical uncertainties)



- $0.0055 \; < \; |V_{td}| \; < \; 0.0271$
- $\lambda_t \; \equiv \; V_{ts}^* \cdot V_{td} \; = \; A^2\lambda^5 \cdot (1 \; - \rho \; - \; i\eta)$: $\quad 0.24 \times 10^{-3} \; < \; |\lambda_t| \; < \; 1.08 \times 10^{-3}$

Conclusions

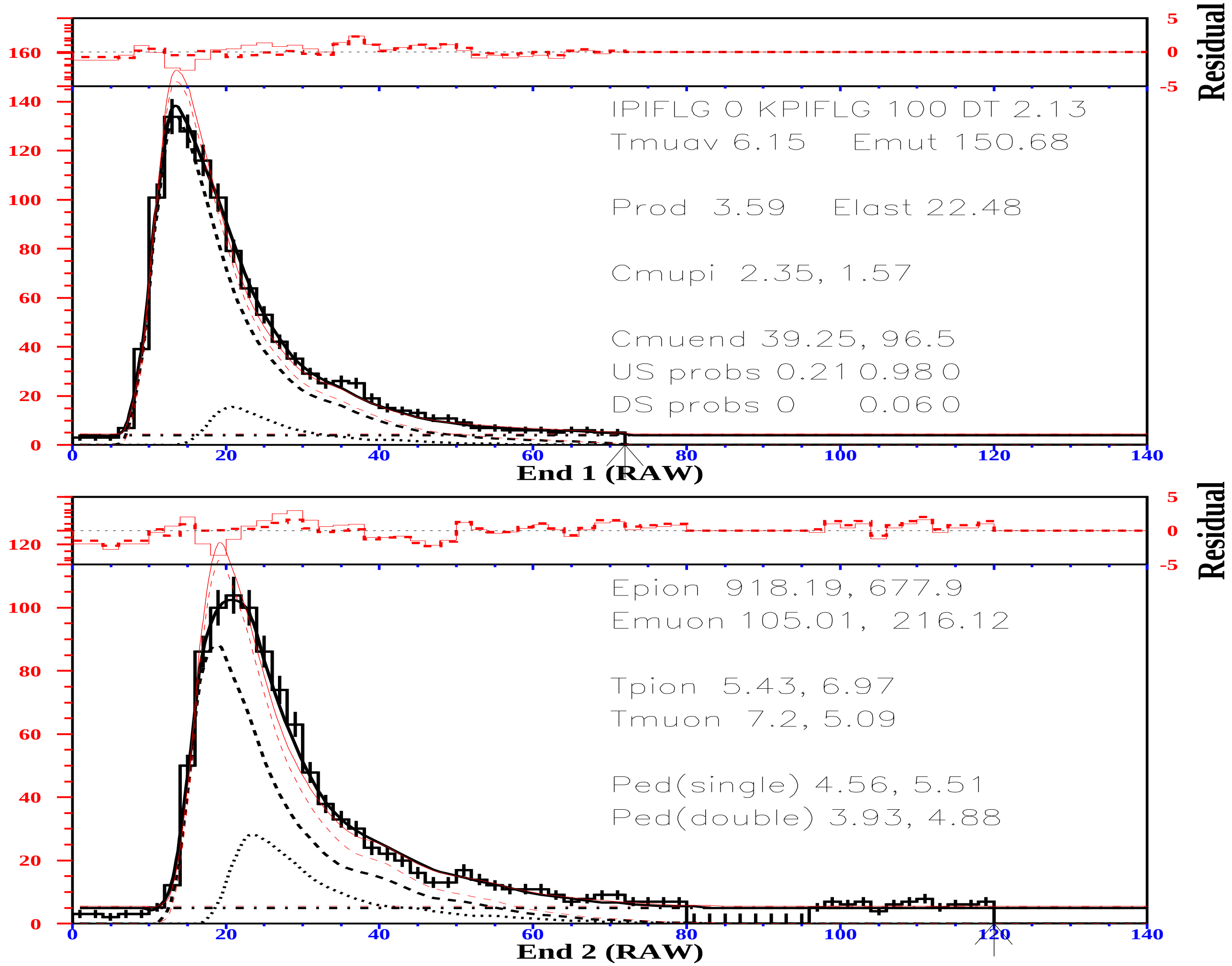
- We succeeded in upgrading E787 to create E949.
- We have proceeded to the stage of Likelihood analysis for studying rare decays
- First Results from E949 on $\mathbf{K^+ \to \pi^+ \nu \bar{\nu}}$:
  - an additional candidate event
  - B.R.$(\mathbf{K^+ \to \pi^+ \nu \bar{\nu}}) = \mathbf{1.47^{+1.30}_{-0.89} \times 10^{-10}}$ for the combined data of E787 and E949
  - constraints on Unitarity Triangle (or violation ?? if the central value is correct)

Future

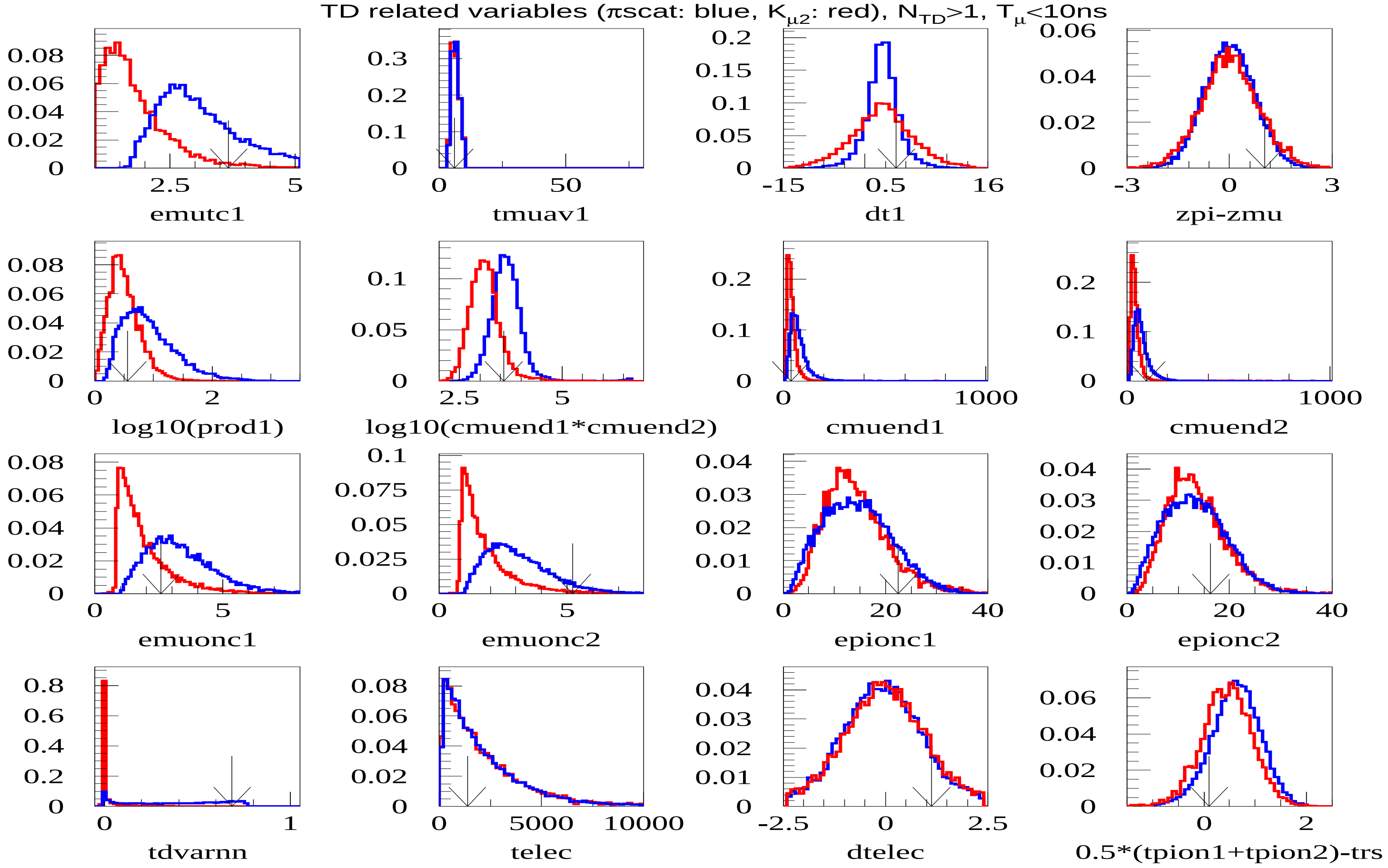
- Proton operations at AGS (by US-DOE) halted for FY2003.
  $\rightarrow$ no new E949 data since then
- Analyses for other K^+ decay modes
  (including $\mathrm{K}^+ \rightarrow \pi^+ \nu\bar{\nu}$ for $P_{\pi^+} < 195$ MeV$/c$)
  are in progress.
- A proposal to continue running E949 has been submitted to the National Science Foundation of the US.
- We need more statistics; the show must go on !
  - K^+ decay at rest @ J-PARC
  - K^+ decay in flight @ FNAL, CERN

backup slides

Pulse fitting in stopping counter



Compare TD properties of candidate with π^+ and μ^+ samples



Quantities related to pion particle identification from TD variables. Events with similar background rejection and fitted muon time < 10 ns are selected. The pion signal (blue) and the muon background (red) are shown in the same plots. The arrows indicate the positions of the candidate event.