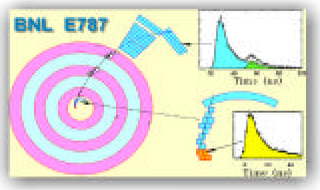


E949 and Measurement of the $K^+ \rightarrow \pi^+ \nu \nu$ Branching Ratio

E949 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

BROOKHAVEN NATIONAL LABORATORY

Steve Kettell , BNL

December 8th, 2004

Princeton HEP Seminar

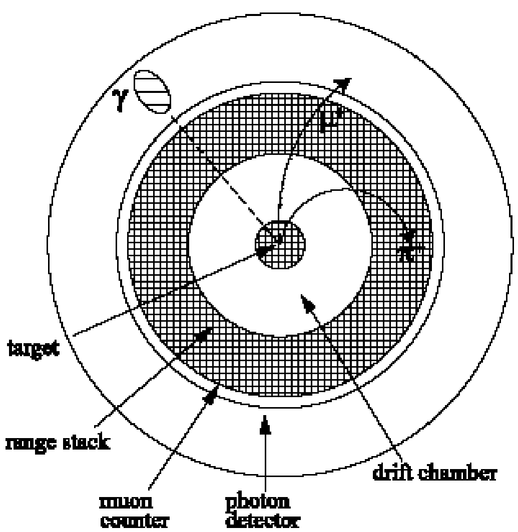
I. Why is $K^+ \rightarrow \pi^+ \nu \nu$ interesting?

II. Overview of $K^+ \rightarrow \pi^+ \nu \nu$.

III. Details about E949.

IV. Conclusions.

JPARC L-04



u c t

CKM

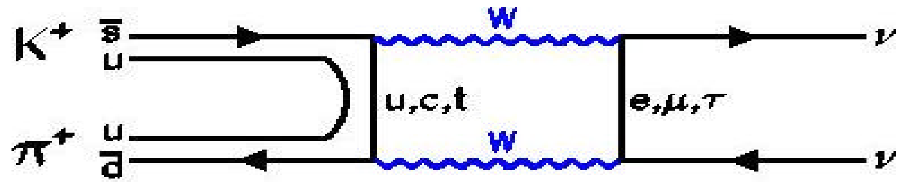
d s b

E921/P940

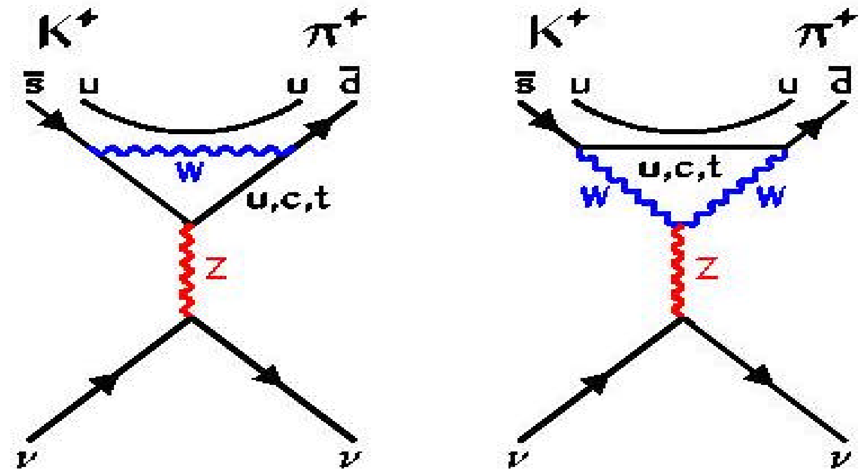
NA48

NA48-3

$K^+ \to \pi^+ \nu \nu$ Motivation

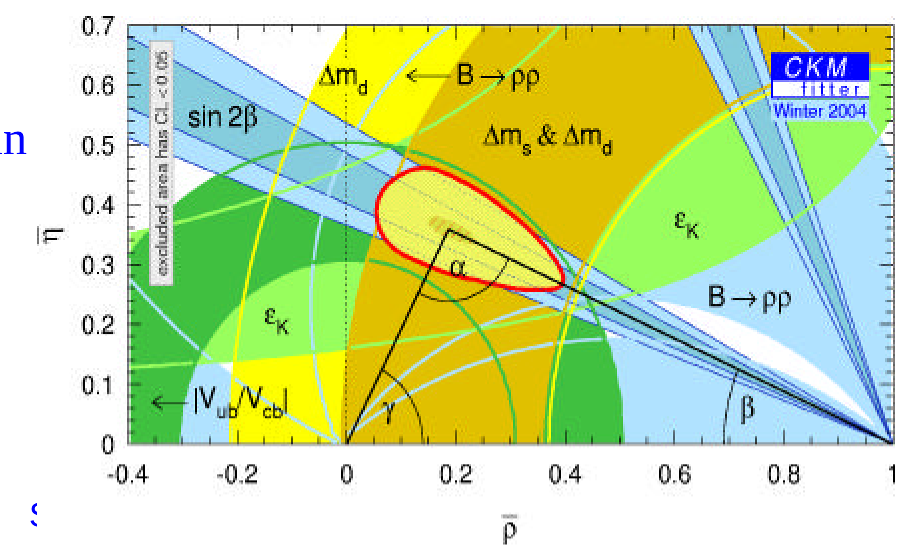


One of the Golden Modes for study of the CKM matrix and CP violation. The rate can be calculated precisely from fundamental SM parameters (~8%), and any deviation in the measured rate will be a clear signal for new physics.



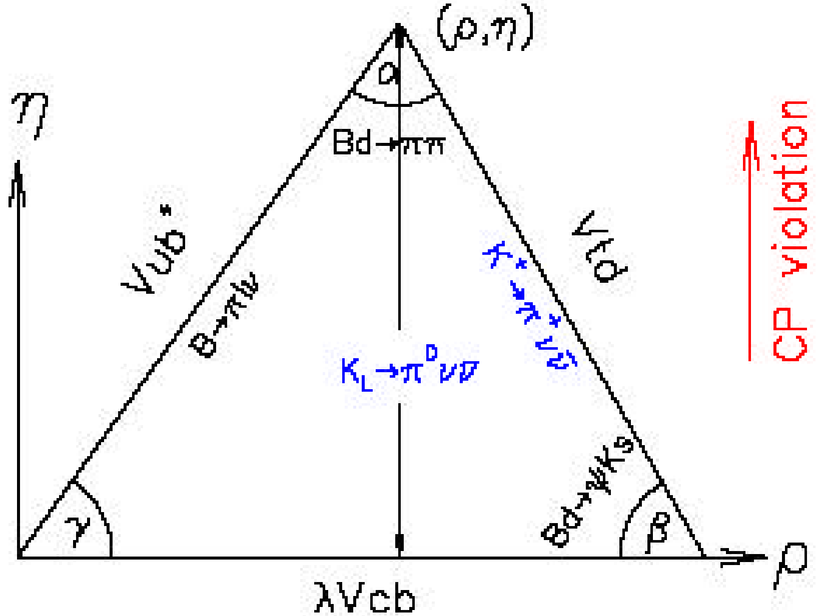
1. FCNC, hard GIM suppression
2. No long distance contribution
3. Hadronic Matrix element from Ke3/isospin
4. NLO QCD calculation of c-quark cont.
5. $B(K^+ \to \pi^+ \nu\nu) = (0.8 \pm 0.1) \times 10^{-10}$

hep-ph/0405132



Unitarity Triangle

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



Four super-clean processes

Process	Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	E787/E949, FNAL-E921
$\mathcal{B}(K^0_L \to \pi^0 \nu\bar{\nu})$	KOPIO, E391a
$\mathcal{A}(B \to J/\psi K^0_S)$	BaBar, Belle

CP violating decay rate asymmetry

$\Delta M_{B_s}/\Delta M_{B_d}$	CDF, D0, LHCb, BTeV

ratio of mixing frequencies of B_s and B_d mesons

Perhaps the most incisive test of the SM picture of CP violation is to verify $b_{yK}=b_{pnn}$ from A(B_d ® J/ø $Ê_s^o$) & B(K_L® ð^{ï}íí)/B(K^+® ð$^+$íí)

Y. Grossman @ FNAL Proton Driver Workshop 10/7/04

Why is $K \to \pi\nu\bar{\nu}$ so clean?

The general problems with hadronic decays are:

- Hadronic matrix elements $\Leftarrow$ Isospin
- Long distance effects $\Leftarrow$ Neutrinos

Therefore the $K \to \pi\nu\bar{\nu}$ decays are very interesting

- Exclusive hadronic decays that we can calculate in the SM and its extensions
- The measured rates are sensitive to fundamental parameters

Y. Grossman $K \to \pi\nu\bar{\nu}$ in and beyond the SM Fermilab, 10/7/04 – p.6

$K^+ \to \pi^+ \nu\nu$ Motivation (cont)

- Motivation for, and interest in, $K^+ \to \pi^+ \nu\nu$ remains high
  - PL**B530**(2002)108: *K^+®p^+nn, A rising star on the stage of flavor physics*
  - JHEP05(2003)053: *Shedding Light on the `Dark Side' of B-mixing… K®pnn*
  - NP**B660**(2003)225: *The Impact of Universal Extra Dimensions on the Unitarity Triangle and Rare K and B Decays*
  - NP**B697**(2004)133: *Anatomy of Prominent B and K Decays and Signatures of CP Violating New Physics in the Electroweak Penguin Sector*
  - hep-ph/0402191: *Waiting for Clear Signals of New Physics in B and K Decays*
  - hep-ph/0404229: *K^+®p^+nn and FCNC from non-universal Z' Bosons*
  - hep-ph/0405132: *Waiting for Precise Measurements of K^+®p^+nn and K_L®p^0nn*
  - hep-ph/0407021: *Constraints on New Physics from K®pnn*
  - hep-ph/0407216: *K®pnn from standard to new physics*
  - hep-ph/0408125: *K_L®p^0nn in Little Higgs model*
  - PL**B588**(2004)74: *Lepton Flavor Mixing and K®pnn Decays*
  - hep-ph/0408142: *K^+®p^+nn and K_L®p^0nn Decays in the General MSSM*

$K^+ \to \pi^+ \nu\nu$ Beyond the Standard Model

- New Physics is likely to affect K's and B's differently

	K^+ ® p^+nn	**K_L ® p^0nn**
SM (hep-ph/0405132)	**(7.8±1.2)´10^{-11}**	**(3.0±0.6)´10^{-11}**
MFV (hep-ph/0310208)	19.1×10^{-11}	9.9×10^{-11}
EEWP (N**PB697**:133)	$(7.5\pm2.1)\times10^{-11}$	$(3.1 \pm 1.0)\times10^{-10}$
EDSQ (hep-ph/0407021)	15×10^{-11}	10×10^{-11}
MSSM (hep-ph/0408142)	40×10^{-11}	50×10^{-11}

Enhanced Electroweak Penquins: Buras SUSY04

Implications for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

$Br(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (7.8 \pm 1.2) \cdot 10^{-11}$ ➡ $(7.5 \pm 2.1) \cdot 10^{-11}$ ⬅ Enhancement of |X| compensated by destructive "top-charm" interference

☆ $Br(K_L \to \pi^0 \nu\bar{\nu})_{SM} = (3.0 \pm 0.6) \cdot 10^{-11}$ ➡ $(3.1 \pm 1.0) \cdot 10^{-10}$

☆ Strong Violation of the "Golden" Relation (Buchalla, AJB (94)) :

SM: $(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_S}$

Here: $-\left(0.69^{+0.23}_{-0.41}\right) \neq 0.74 \pm 0.05$

$\sin 2\beta_X$

$\beta_X = \beta - \theta_X$

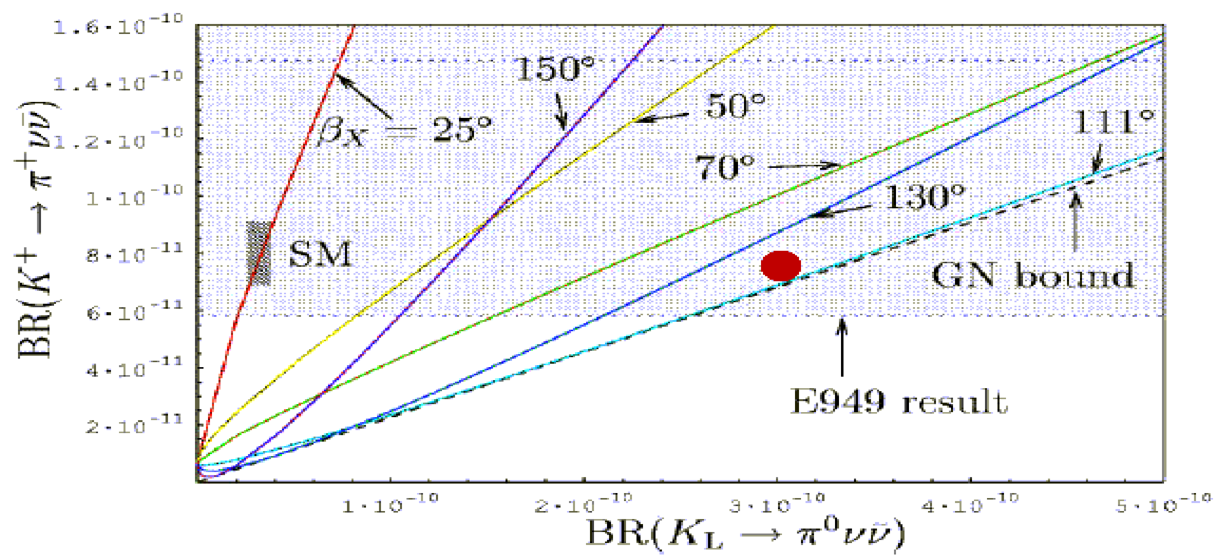
$X = |X| e^{i\theta_X}$

$\beta_X \approx 110^\circ$

☆ FIG Saturation of the model-independent Grossman-Nir bound :

$Br(K_L \to \pi^0 \nu\bar{\nu}) \leq 4.4 \; Br(K^+ \to \pi^+ \nu\bar{\nu})$

Here: $\frac{Br(K_L \to \pi^0 \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})} \approx 4.4 \; \sin^2(\beta_X) \approx 4.2 \pm 0.2$

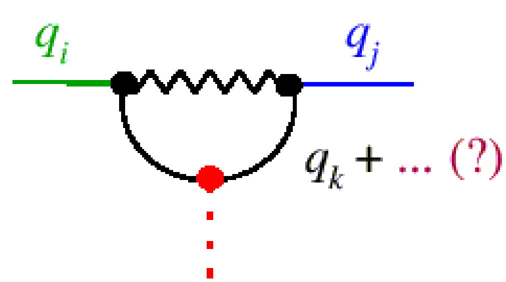


G. Isidori at the SPSC Villars Meeting 9/28/04

Precision studies of rare decays can (slightly) improve our knowledge of the CKM matrix but their main interest is in probing the flavour structure of new physics:

Rare processes mediated by
Flavor Changing Neutral Currents
are the ideal candidates

$q_i \rightarrow q_j + \gamma,\ l^+l^-,\ \nu\bar{\nu}$



no SM tree-level contribution

strong suppression – within the SM – by CKM hierarchy

calculable with high precision within the SM if dominated by short-distance dynamics [*key point*]

precise determination of flavor mixing within the SM

enhanced sensitivity to
[*the flavour structure of*]
physics beyond the SM

G. Isidori at the SPSC Villars Meeting 9/28/04

Neutrino modes:

Hadronic matrix element of the leading operator directly extracted from K_{l3}

No sizable long distance corrections [only Z-penguin & W-box ⇒ hard GIM suppression effective also for the leading l.d. terms]

Dominant uncertainty from the perturbative charm contribution [NNLO corr.] + subleading long distance terms [power-suppressed higher-dim. operators]

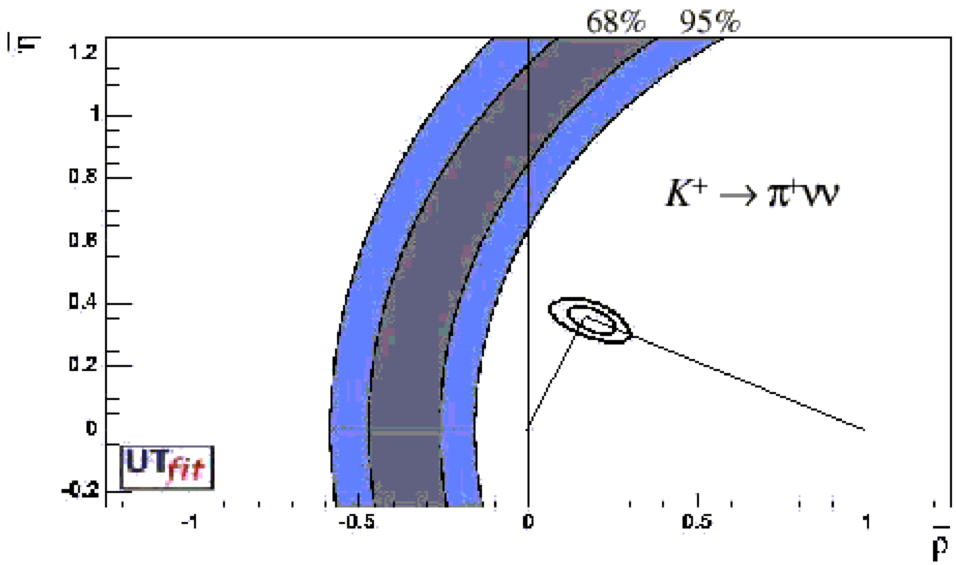
$K^+ \to \pi^+ \nu\nu$ $\mathrm{BR}(K^+)^{[SM]} = C\,|V_{cb}|^4 [(\bar\rho - \rho_c)^2 + (\sigma\bar\eta)^2] = (8.0 \pm 1.0)\cdot 10^{-11}$

if we could decrease the error at the 10% level...

$\mathrm{BR}(K^+)^{exp} = (1.47^{+1.9}_{-0.9})\cdot 10^{-10}$ (uncertainty crossed out)

↓

±10% →



The situation could become quite interesting...

G. Isidori at the SPSC Villars Meeting 9/28/04

Th. error ≲ 10% decreasing SM contrib. →

decreasing SM contrib. ↓

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
ΔF=2 box	ΔM_d $A_{CP}(B_s \to \psi K)$	ΔM_s $A_{CP}(B_s \to \psi\phi)$	ΔM_K ε_K
ΔF=1 4-quark box	$B_d \to \pi K$, $B_d \to \eta K$, $A_{CP}(B_d \to \phi K)$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, $A_{CP}(B_d \to \pi\pi)$, ...	ε'/ε, $A_{CP}(K \to 3\pi)$, ...
gluon penguin	$B_d \to X_s\gamma$ $B_d \to \pi K$, $A_{CP}(B_d \to \phi K)$, ...	$B_d \to X_d\gamma$ $B_d \to \pi\pi$, $A_{CP}(B_d \to \pi\pi)$, ...	$K_L \to \pi^0 l^+ l^-$, ε'/ε, ...
γ penguin	$B_d \to X_s l^+ l^-$ $B_d \to X_s\gamma$ $B_d \to \pi K$, $B_s \to KK$, ...	$B_d \to X_d l^+ l^-$, $B_d \to X_d\gamma$ $B_d \to \pi\pi$, $B_s \to \pi K$, ...	$K_L \to \pi^0 l^+ l^-$, ε'/ε, ...
Z^0 penguin	$B_d \to X_s l^+ l^-$ $B_s \to \mu^+\mu^-$ $B_d \to \pi K$, $B_s \to KK$, ...	$B_d \to X_d l^+ l^-$, $B_d \to \mu^+\mu^-$ $B_d \to \pi K$, $B_s \to KK$, ...	$K_L \to \pi^0 l^+ l^-$, $K_L \to \pi^0 \nu\nu$ $K^+ \to \pi^+ \nu\nu$, ε'/ε, ...
H^0 penguin	$B_s \to \mu^+\mu^-$	$B_d \to \mu^+\mu^-$	$K_{L,S} \to \mu^+\mu^-$

(filled) = exp. error ≲ 10% (open) = exp. error ~ 30-50%

CERN SPSC: M. Mangano at Villars 9/28/04

Conclusion for K's

Absolutely clear physics case, to be pursued with the strongest determination in a global context of healthy, aggressive and very competent competition

The discovery of Supersymmetry at the LHC will dramatically increase the motivation for searches of **new phenomena in flavour physics.**

The K physics programme will find a natural complement in the B physics studies at the LHC, and in new Lepton Flavour Violation searches.

The definition of a potential LFV programme and the study of its implications for the accelerator complex should be strongly encouraged and supported

Is $K^+ \rightarrow \pi^+ \nu\nu$ Interesting?

- Cessation of DOE funding for E949 operations
- P5 rejection of CKM

Evaluation – The subpanel was impressed with the excellent work of the proponents on the design of the experiment and their successful prototyping results. CKM is an elegant world-class experiment, which would be able to produce important physics results. However, the committee assigns it a lower priority than the BTeV experiment. The main reason is that BTeV has a much broader physics program at a comparable cost.

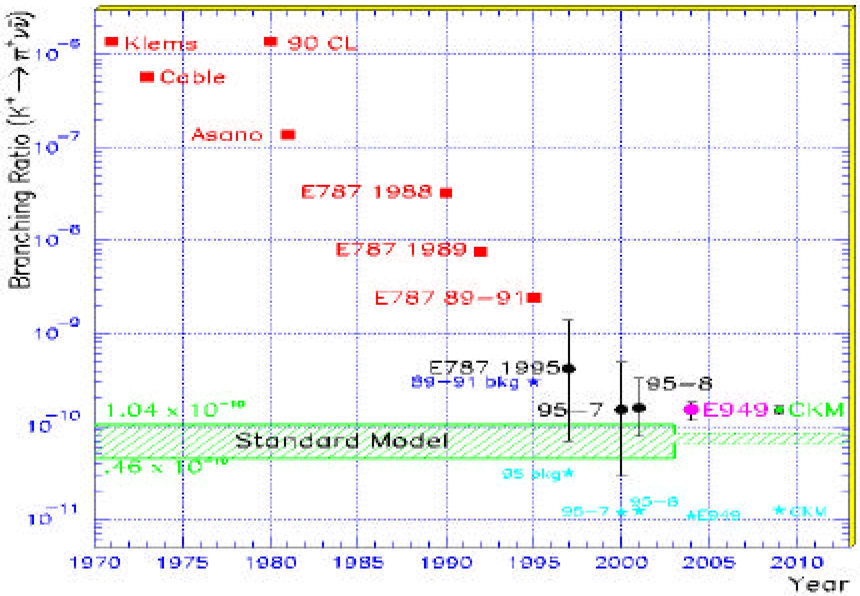
Suggestions Based on Prioritization – The present Fermilab plan calls for a similar funding profile and time-line for BTeV and CKM construction, with both starting to take data around 2009. The P5 Subpanel believes that this plan is likely to be too ambitious given the need to optimize the physics from the Tevatron Collider, as well as the desire to have BTeV completed promptly. *Based on current budgetary models, P5 does not recommend proceeding with CKM.*

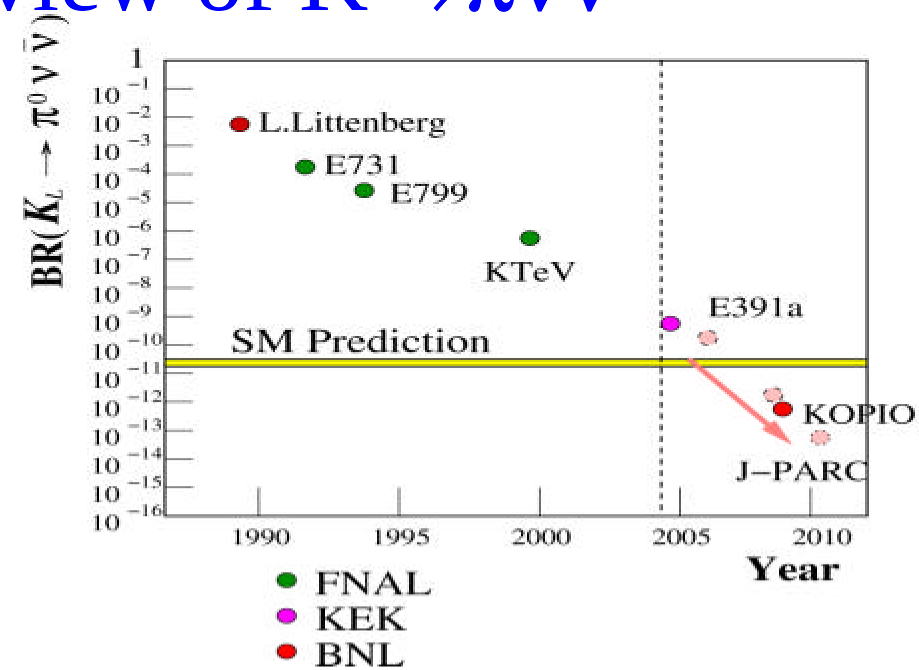
→Should one conclude that $K^+ \rightarrow \pi^+ \nu\nu$ is not important? Or a necessary component of the study of flavor physics and CP violation?

→Are B's (Babar, Belle, LHC-b and BTeV) and $K_L \rightarrow \pi^0 \nu\nu$ (KOPIO, E391) sufficient?

→ Cannot test $\mathbf{b_{yK} = b_{pnn}}$ without $K^+ \rightarrow \pi^+ \nu\nu$

Worldwide Overview of K→πνν

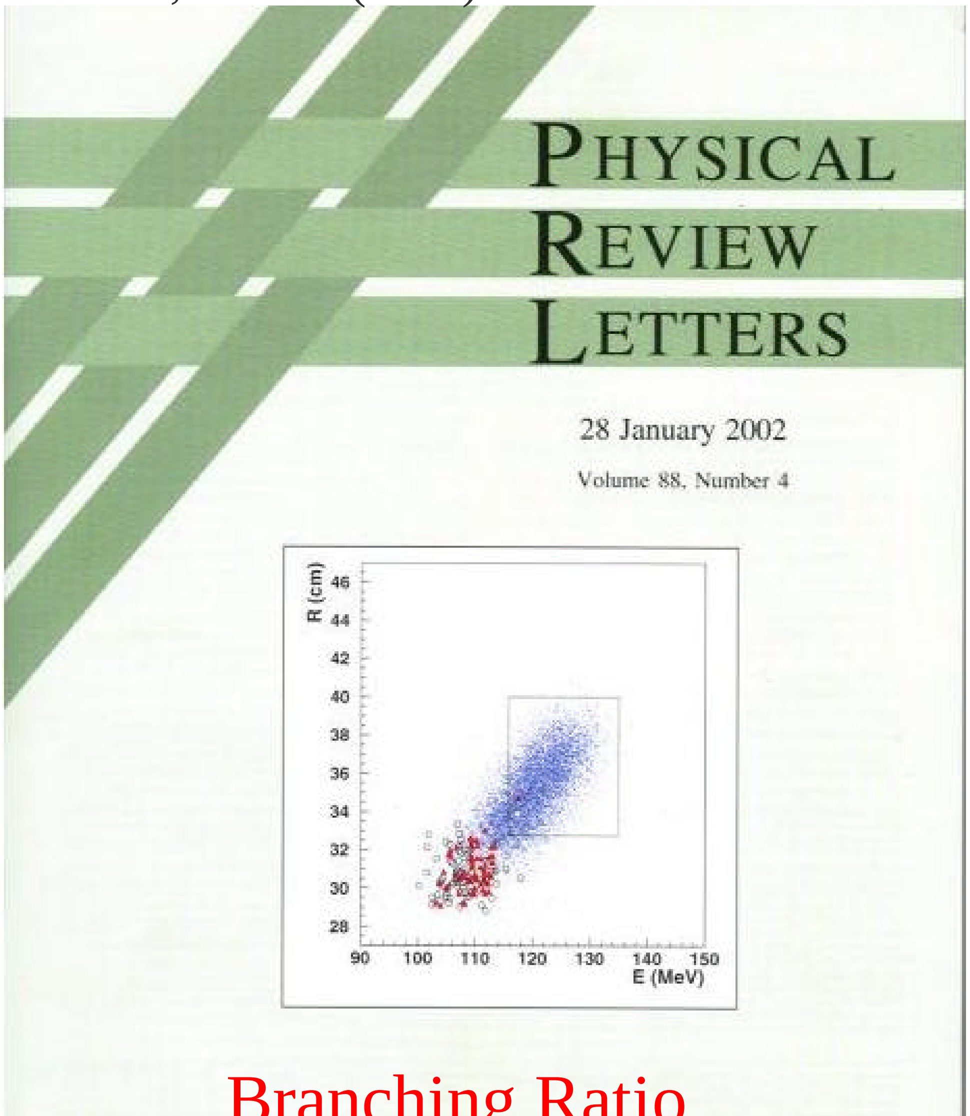


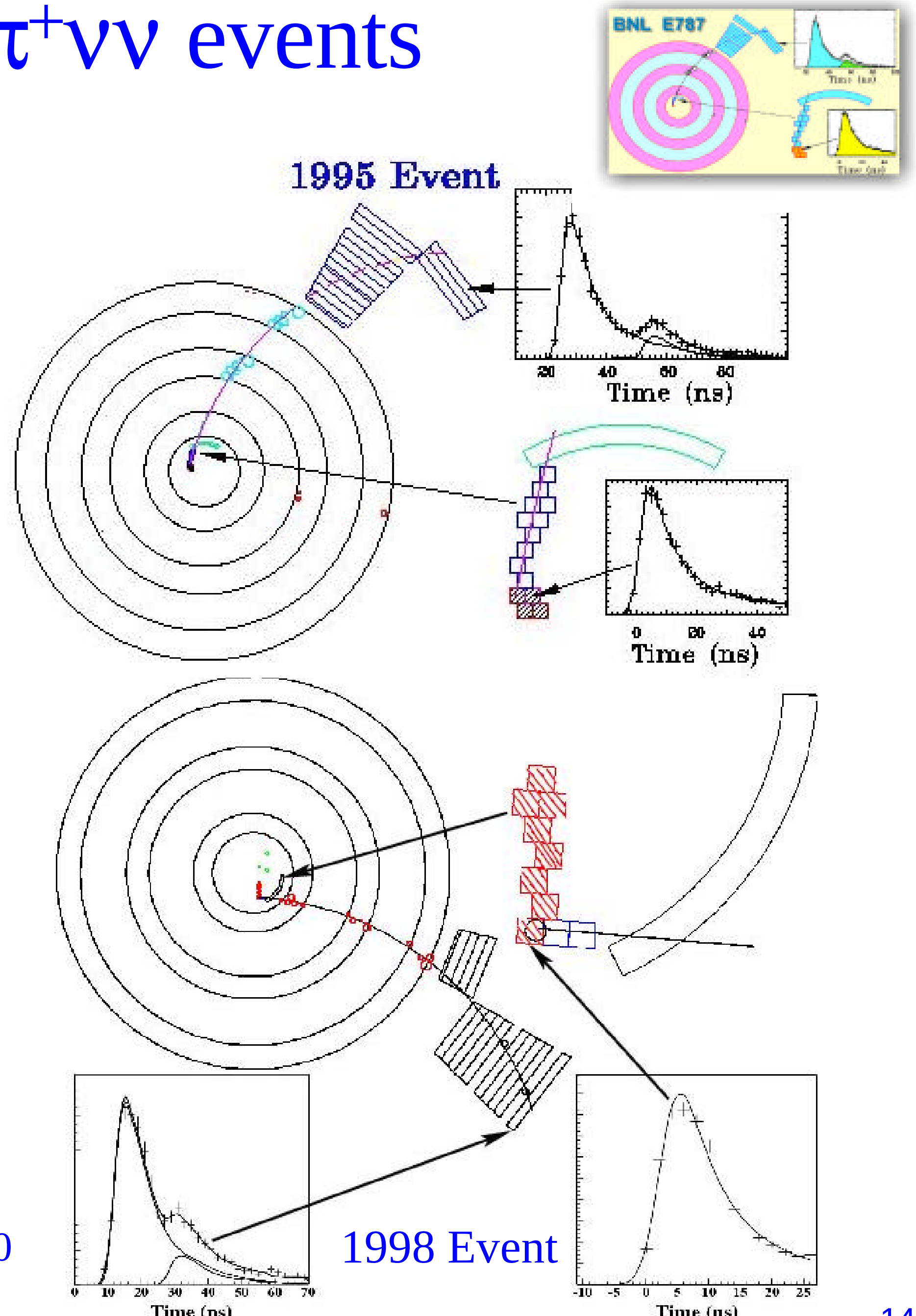


- E787: completed (1988-98); discovered 2 $K^+ \to \pi^+ \nu\nu$ events (DAR)
- E949: 2002 run; approved but not funded for 50 more weeks…(DAR)
- CKM: FNAL scientific approval; P5 says no (separated DIF)
- P940: EOI at FNAL for unseparated DIF
- LOI's:JPARC L-04 (DAR) and CERN NA48-3 (unseparated DIF)
- E391a aims for 0.01-0.1 $K_L \to \pi^0 \nu\nu$ events. E391b LOI for 1000 events
- KOPIO construction start in 2005, aim for 40 $K_L \to \pi^0 \nu\nu$ events

PRL **88**, 041803 (2002)

E787 $K^+ \rightarrow \pi^+ \nu\nu$ events





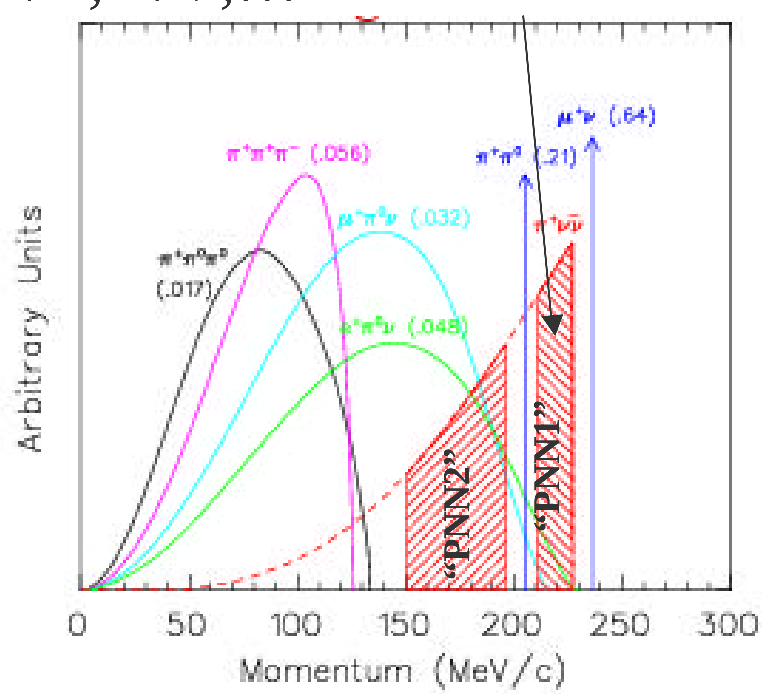
Branching Ratio

$$B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 1.57 \pm^{1.75}_{0.82}\ x\ 10^{-10}$$

Outline of $K^+ \to \pi^+ \nu\nu$ Experimental Method

- **Problem: 3-body decay (2 missing ν's); BR<10^{-10}**
- Event signature = single K^+ in, single π^+ out
- Basic concepts
  - Precise and redundant measurement of kinematics
    e.g. Energy (E) / Momentum (P) / Range (R)
  - PID: π-μ-e decay chain and/or P/R, P/V,…
  - Hermetic veto detectors (γ)
- Major backgrounds
  - $K^+ \to \mu^+\nu$ (Br=63%)
    - Kinematics (monochromatic)
    - PID: π^+/μ^+
  - $K^+ \to \pi^+\pi^0$ (Br=21%)
    - Kinematics (monochromatic)
    - Photon veto
  - Scattered beam particles
    - Timing
    - PID: K^+/π^+

Primary signal region

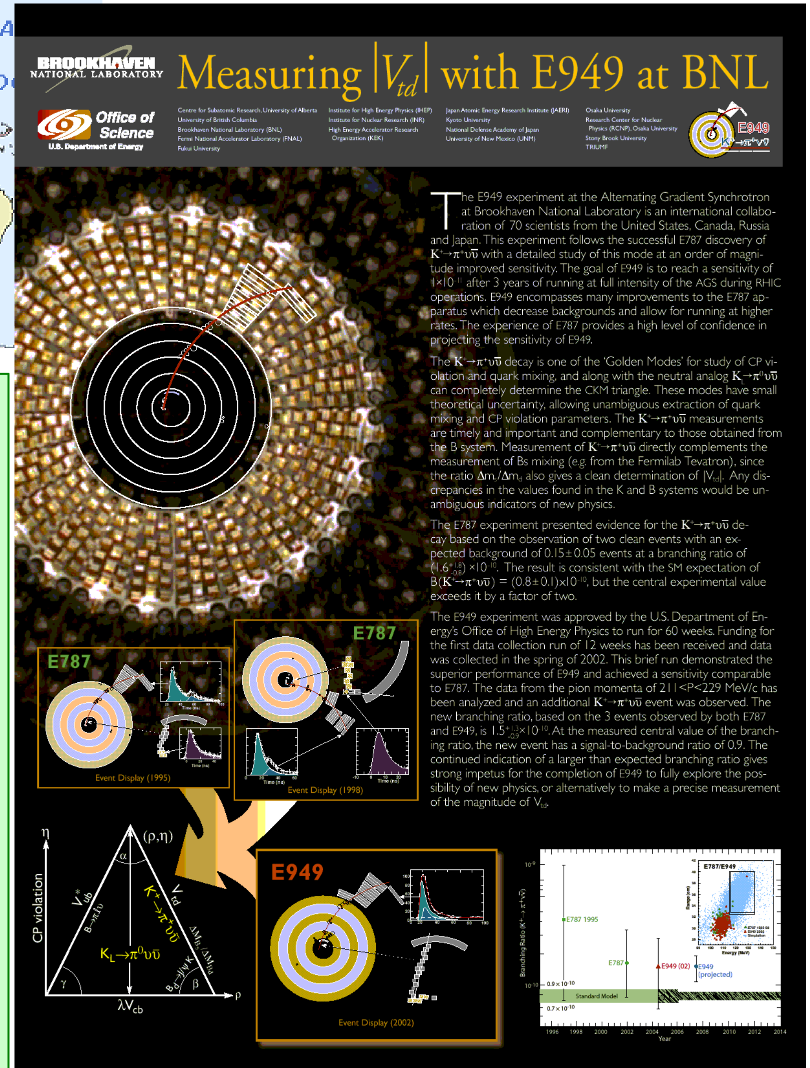


E949 Experiment

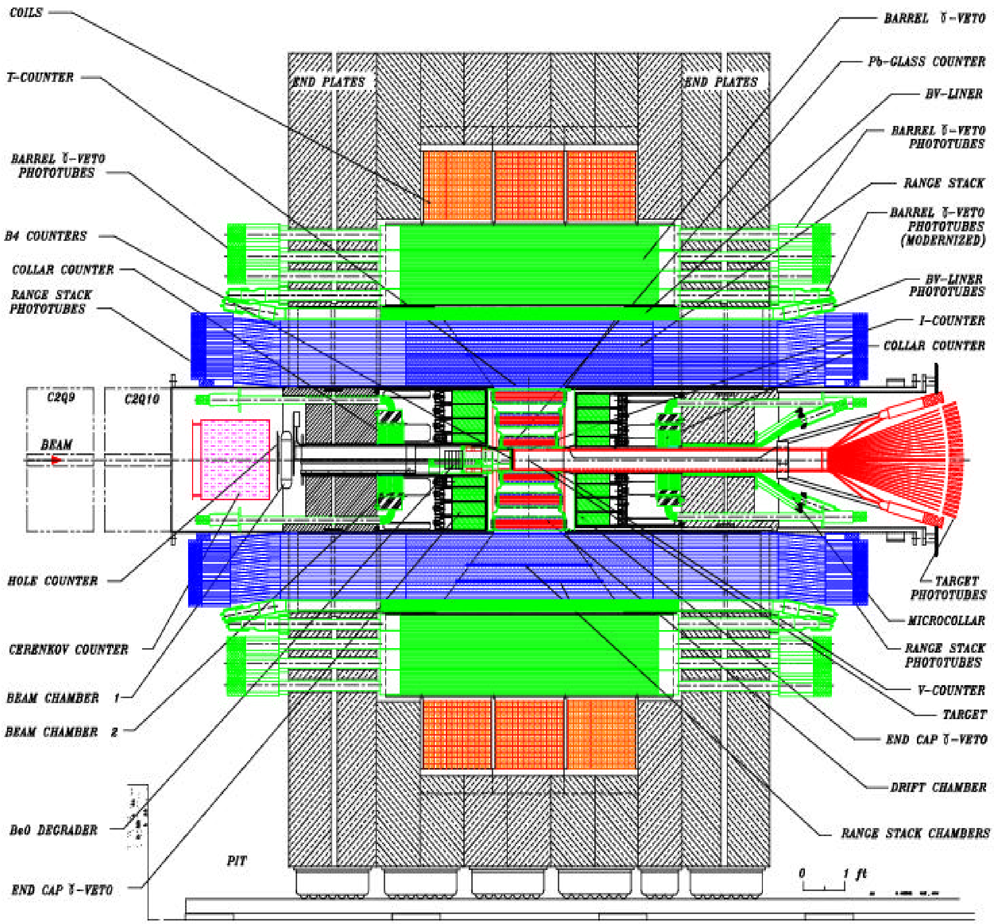
BNL/FNAL/SBU/UNM, U.S.A
IHEP/INR, Russia
Fukui/KEK/Kyoto/NDA/Osaka, Japan
TRIUMF/UA/UBC, Canada

V.V. Anisimovsky[1],A.V. Artamonov[2], B. Bassalleck[3], B. Bhuyan[4], E.W. Blackmore[5], D.A. Bryman[6], S. Chen[5], I-H. Chiang[4], I.-A. Christidi[7], P.S. Cooper[8], M.V. Diwan[4], J.S. Frank[4], T. Fujiwara[9], J. Hu[5], A.P. Ivashkin[1], D.E. Jaffe[4], S. Kabe[10], S.H. Kettell[4], M.M. Khabibullin[1], A.N. Khotjantsev[1], P. Kitching[11], M. Kobayashi[10], T.K. Komatsubara[10], A. Konaka[5], A.P. Kozhevnikov[2], Yu.G. Kudenko[1], A. Kushnirenko[8], L.G. Landsberg[2], B. Lewis[3], K.K. Li[4], L.S. Littenberg[4], J.A. Macdonald[5], J. Mildenberger[5], O.V. Mineev[1], M. Miyajima[12], K. Mizouchi[9], V.A. Mukhin[2], N. Muramatsu[13], T. Nakano[13], M. Nomachi[14], T. Nomura[9], T. Numao[5], V.F. Obraztsov[2], K. Omata[10], D.I. Patalakha[2], S.V. Petrenko[2], R. Poutissou[5], E.J. Ramberg[8], G. Redlinger[4], T. Sato[10], T. Sekiguchi[10], T. Shinkawa[15], R.C. Strand[4], S. Sugimoto[10], Y. Tamagawa[12], R. Tschirhart[8], T. Tsunemi[10], D.V. Vavilov[2], B. Viren[4], N.V. Yershov[1], Y. Yoshimura[10] and T. Yoshioka[10]

1. Institute for Nuclear Research (INR), 2. Institute for High Energy Physics (IHEP), 3. University of New Mexico (UNM), 4. Brookhaven National Laboratory (BNL), 5. TRIUMF, 6. University of British Columbia, 7. Stony Brook University, 8. Fermi National Accelerator Laboratory (FNAL), 9. Kyoto University, 10. High Energy Accelerator Research Organization (KEK), 11. Centre for Subatomic Research, University of Alberta, 12. Fukui University, 13. Research Center for Nuclear Physics (RCNP), Osaka University, 14. Osaka University, 15. National Defense Academy.



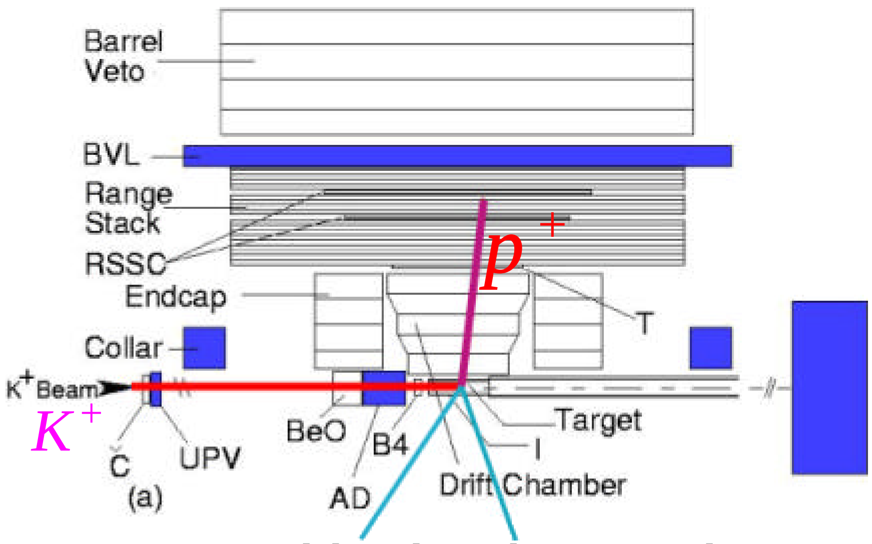
E949 Detector (1): Overview



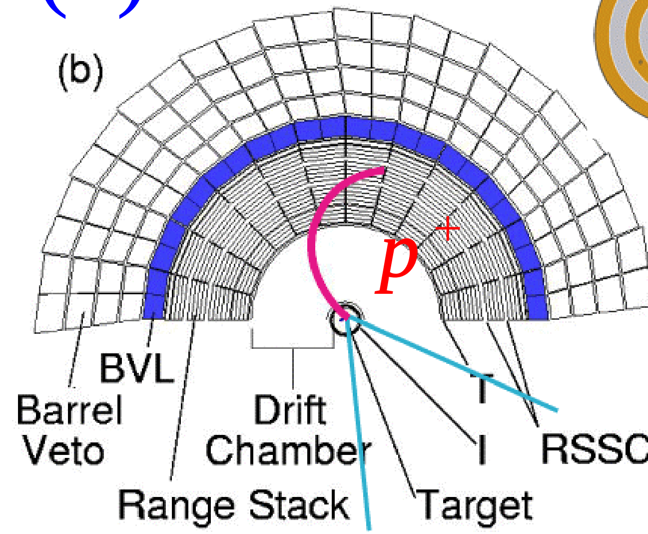
E949 Detector (2): Upgrades

- More protons from the AGS
  - High duty factor, high stopping fraction at low |p|
- Improved photon veto
  - Especially important for pnn2
- Improved tracking and energy resolution
- Higher rate capability from trigger, electronics, DAQ upgrades (reduced deadtime)

E949 Detector (3): Details



Side view (cutaway)



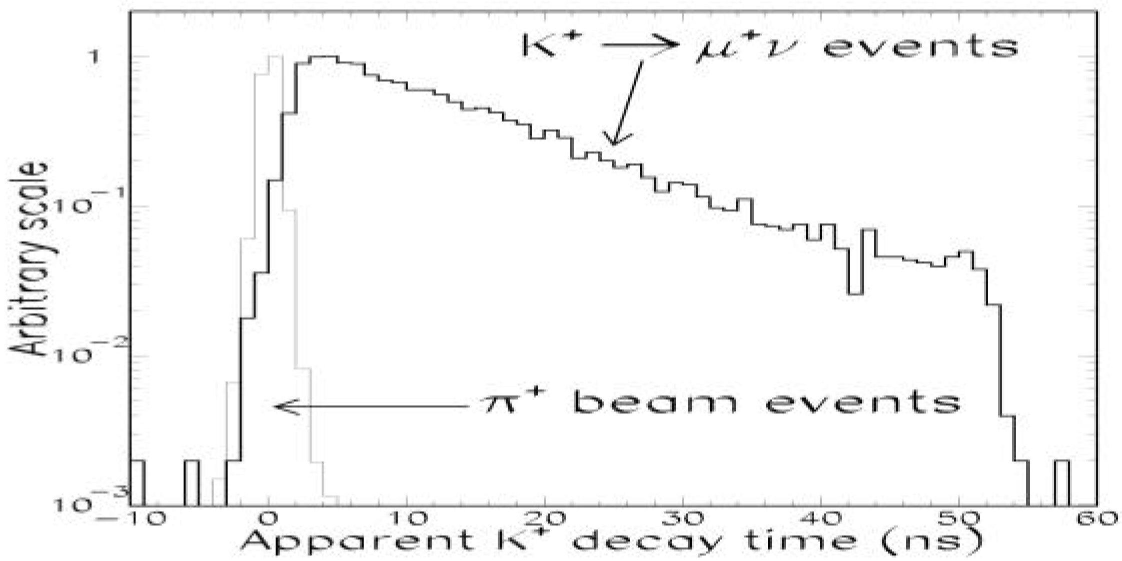
End view (top half)

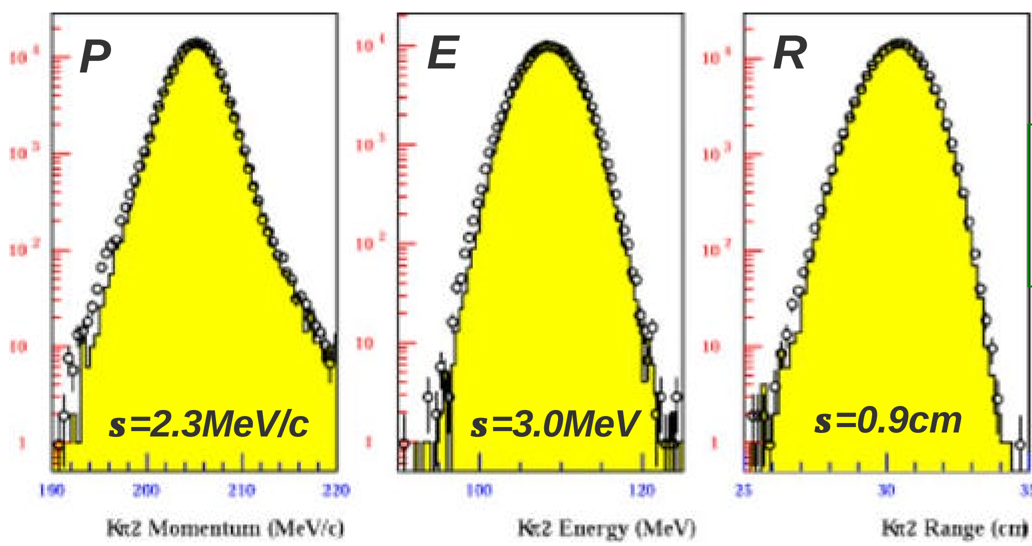
- 700 MeV/c K^+ beam (80%)
- Active target (scintillation fibers) to stop K^+
- Wait at least 2ns for K^+ decay
- Drift chamber to measure π^+ momentum
- 19 layers of scintillator, Range Stack (RS) to measure E and R
- Stop π^+ in RS, waveform digitizer to record π^+-μ^+-e^+ decay chain
- Veto photons, charged tracks over 4π (BV/BVL/Endcap/…)

Renew inner 5 layers!
Equip gain monitor!

New!

Kinematics of $K^+ \to \pi^+ \nu\nu$ at rest





Kp2 momentum, energy and range

E949 (yellow histogram) vs. E787 (circle)

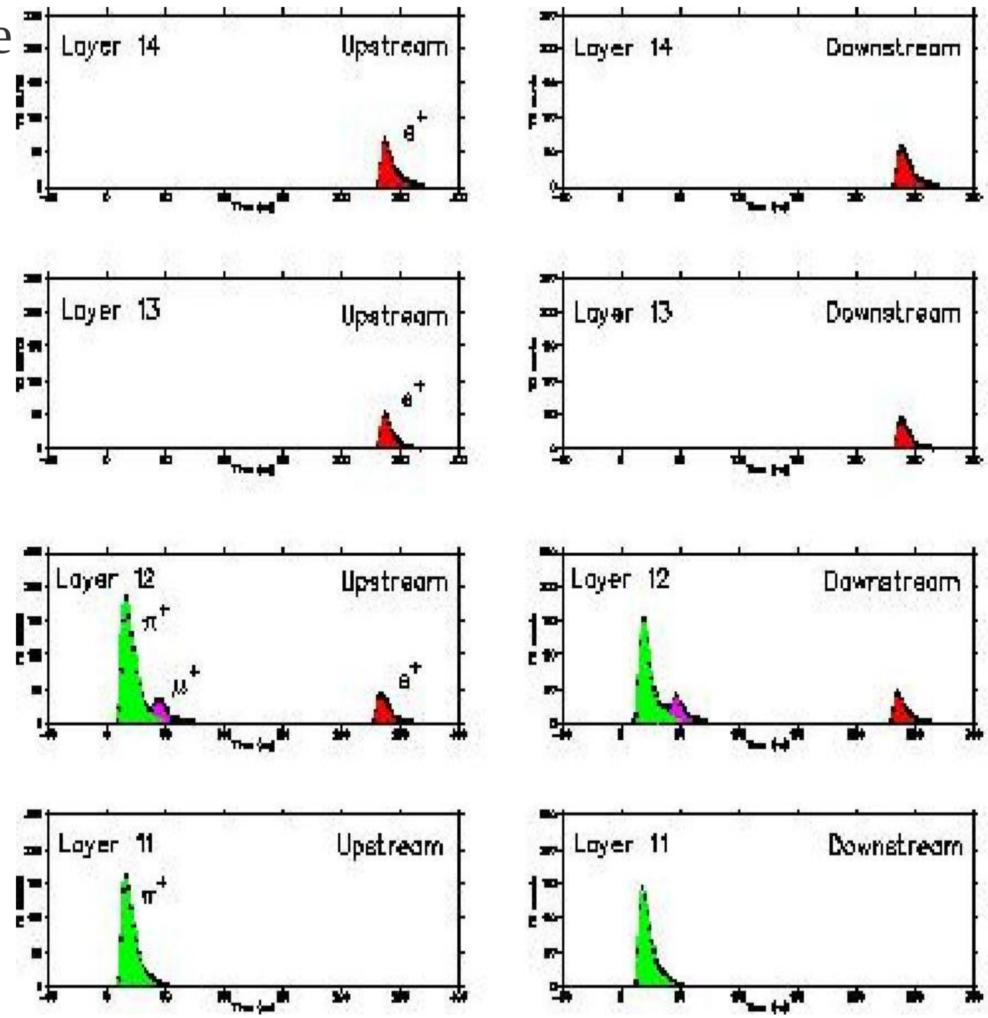
Same or even better resolution in 2 x higher rate environment

Identify $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ (TD)

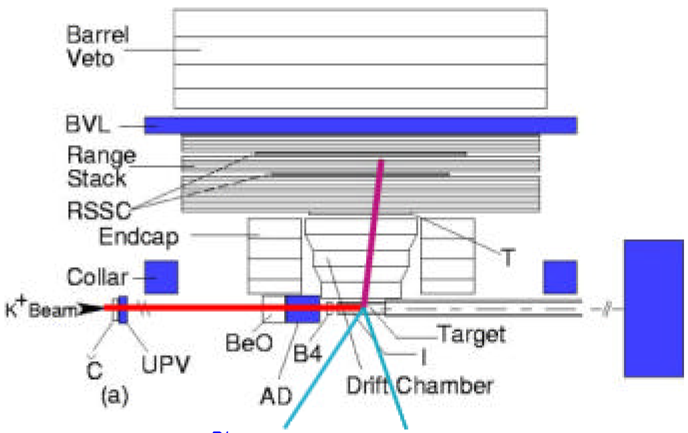
- Transient Digitizers (**TD**'s) sample pulse height every 2ns for 2μs.
- π^+ stops in range stack scintillator (2cm/layer)
- $\pi^+ \rightarrow \mu^+ \nu$, E_μ=4.1 MeV, R_μ =1mm, τ_π=26ns
- $\mu^+ \rightarrow e^+ \nu \nu$, E_e<53 MeV, τ_μ =2.2 μ s

Plots: pulse height (0-256) vs. time (-50-250ns)

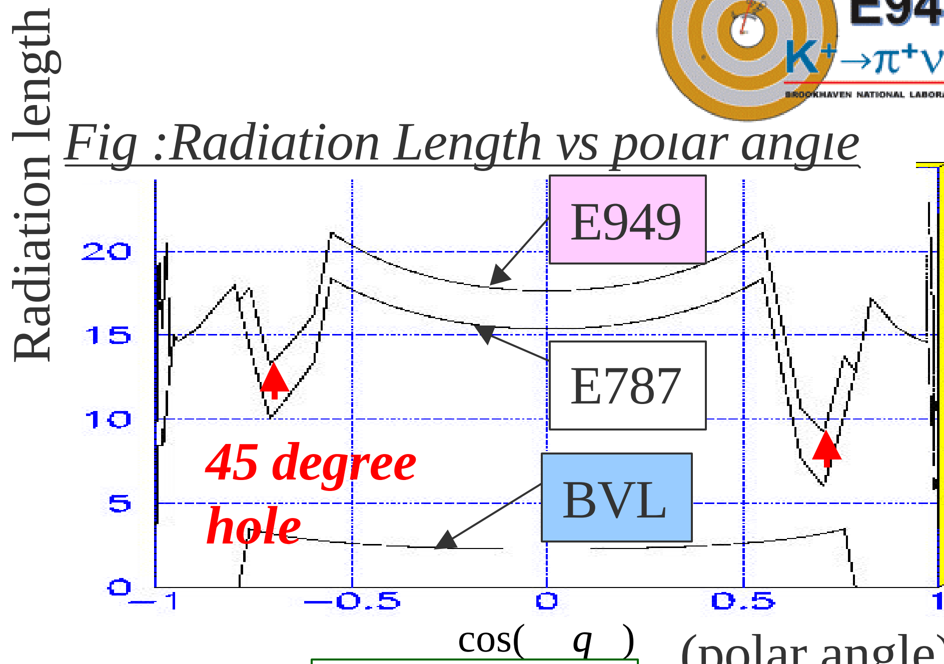
π^+ comes from inner layers and stops in Layer 12, where it decays to a μ^+, which then decays to an e^+ and propagates out to Layer 14.



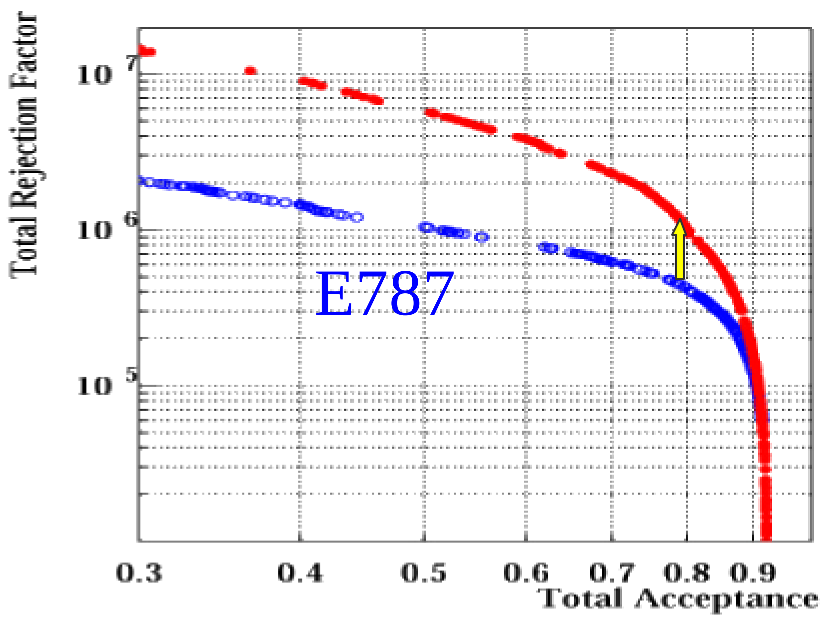
Photon Veto



New ã detectors in blue.



ð^0 rejection

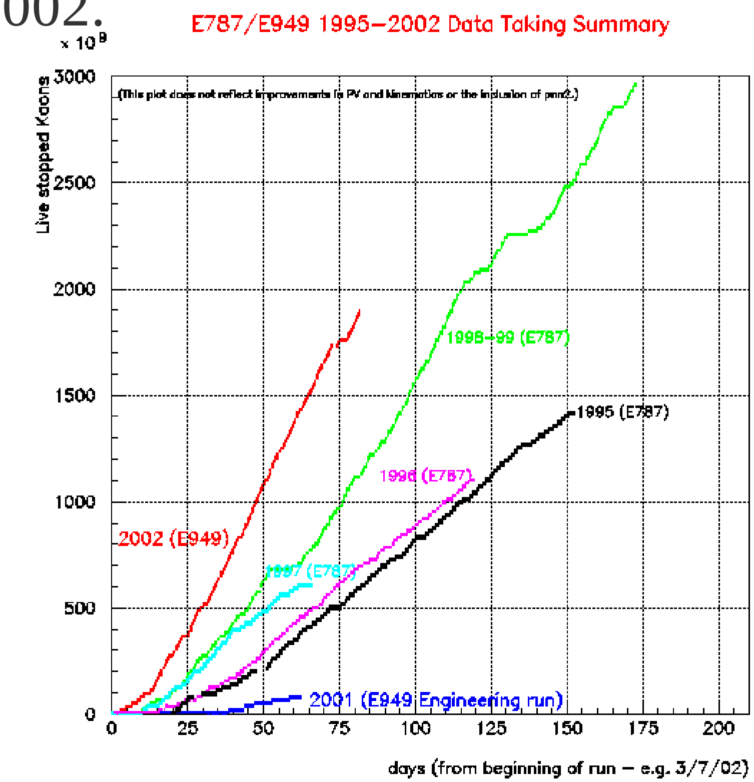


- Rejection of $K_{\pi 2}$ background as a function of acceptance for E787 and E949.
- ×2 better rejection at nominal acceptance (80%)

Data Taking Conditions

- E787 collected N_K=5.9×10[12] in 81 weeks over 5 years.
- E949 proposed N_K=18×10[12] in 60 weeks over 3 years.
- E949 collected N_K=1.8×10[12] in 12 weeks in 2002.
- Beam conditions were not optimized:
  - broken separator – more π^+ less K^+
  - spare M.G. – lower p^+ mom., worse duty factor
- Detector worked very well
- Smooth data taking

	E787	E949 Prop.	E949
AGS mom. GeV/c	25.5	25.5	21.9
Beam intensity Tp	15-35	65	70
Duty factor %	41-55	63	41
K^+/p^+	3.7-4.2	4.0	3.0
N_K 10^{12}	5.9	18	1.8



Analysis Strategy

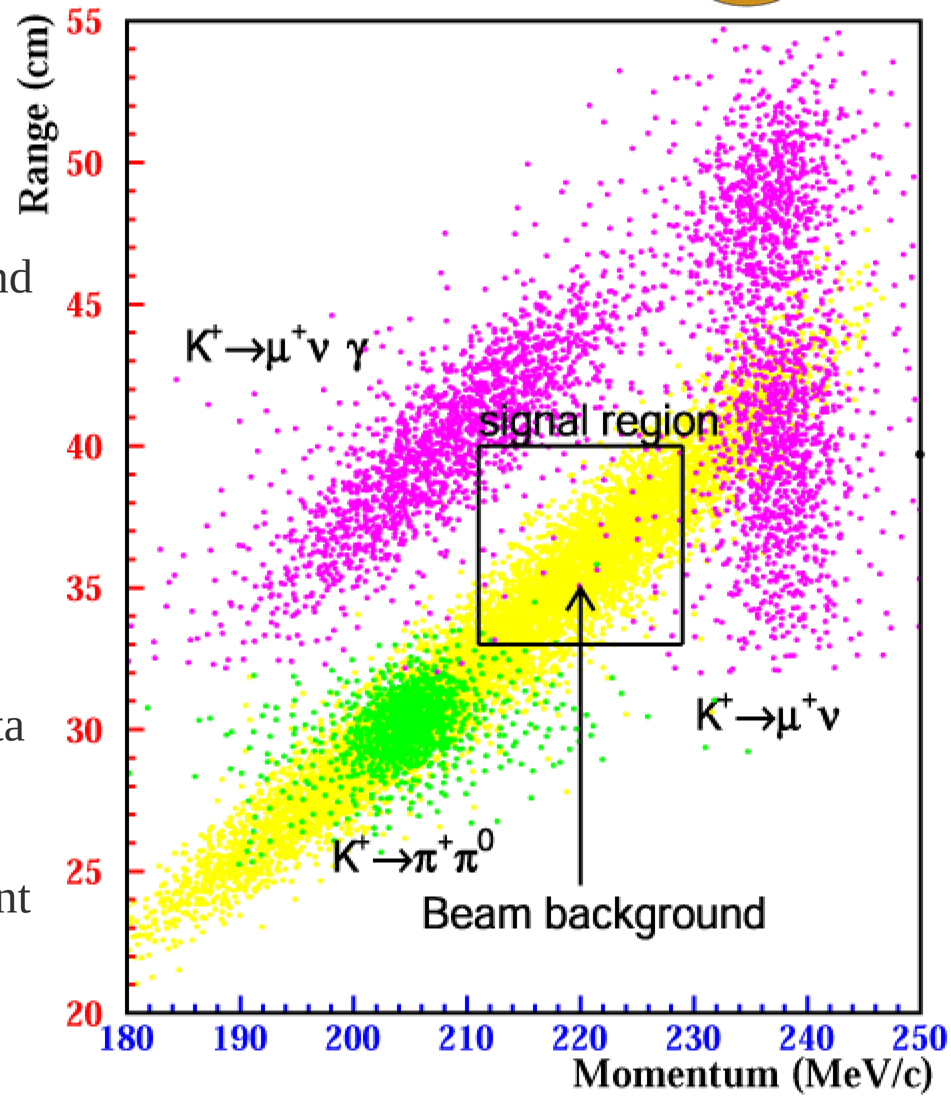
Signal region “the BOX”

Above $K^+ \rightarrow$ ð$^+$ð^0 region (PNN1)

Background sources

Identify *a priori*. Identify at least 2 independent cuts to target each background

- $K^+ \rightarrow$ ð$^+$ð^0
- Muon background ($K^+ \rightarrow m^+ n(g)$)
- Beam background

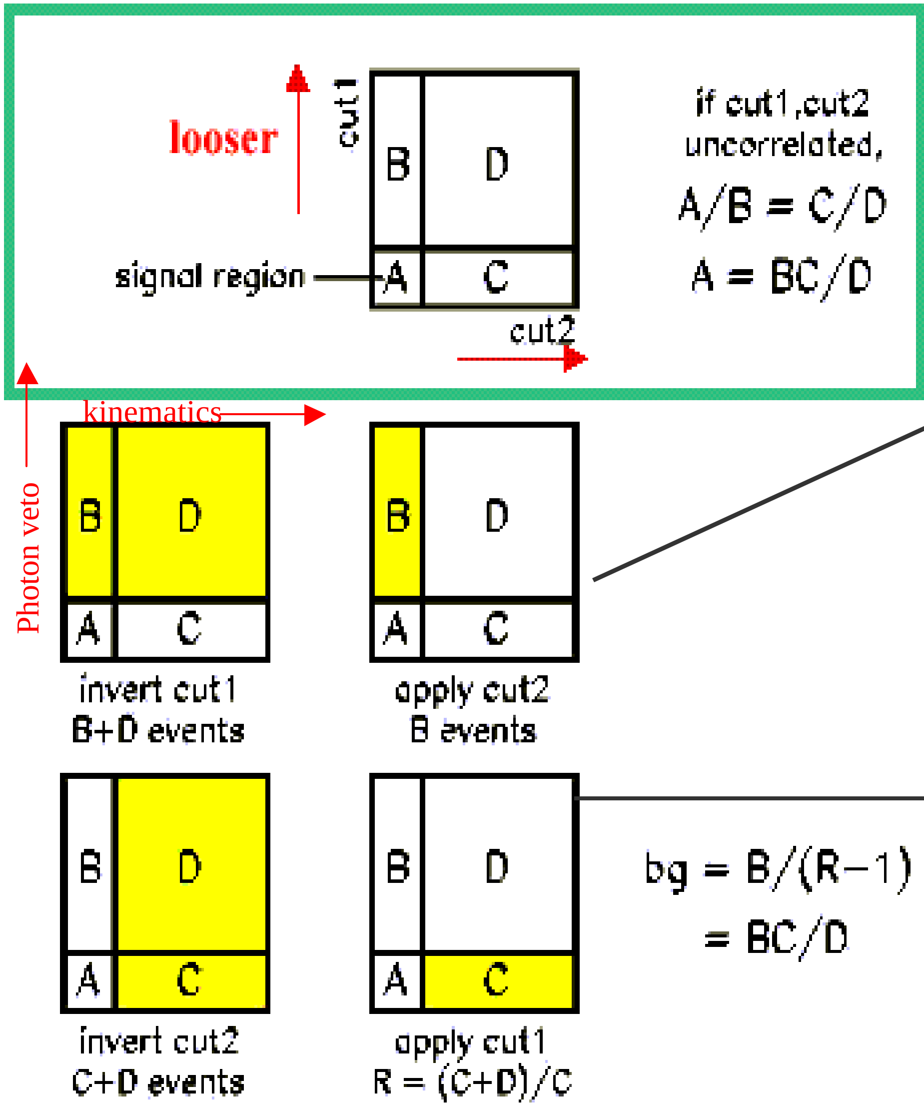


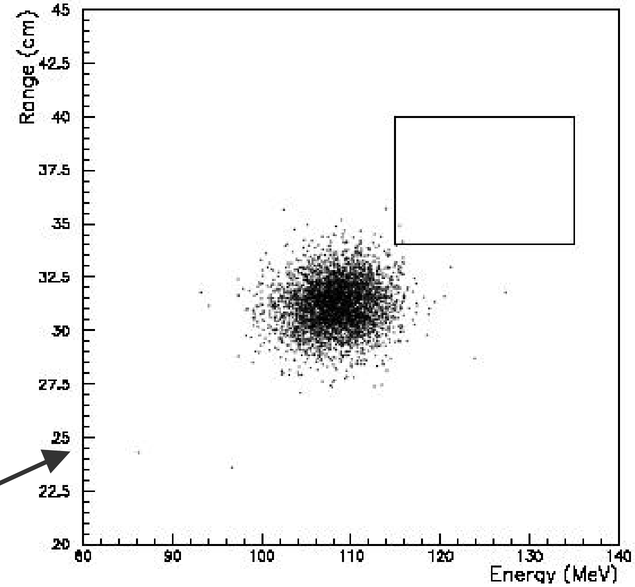
Analysis Strategy

- Blind Analysis
- Measure Background level with real data
- To avoid bias,
  - 1/3 of data ⇒ cut development
  - 2/3 of data ⇒ background measurement
- Characterize backgrounds using back-ground functions
- Likelihood Analysis

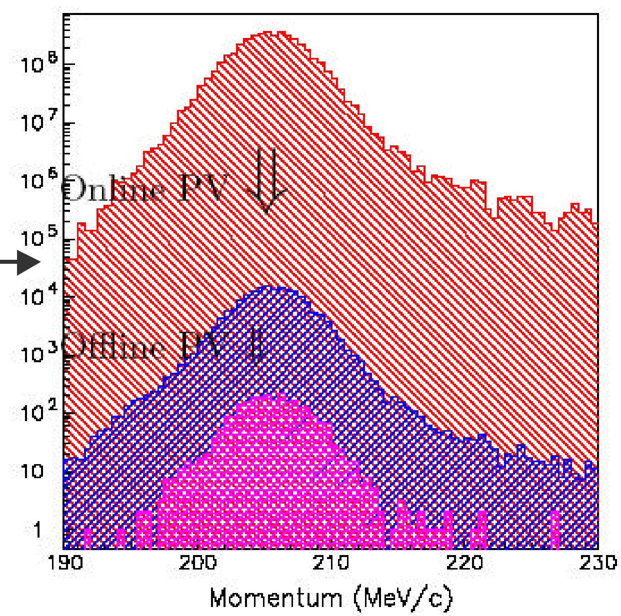
Calculation of backgrounds

Illustration of Bifurcation Method





Tag with γ



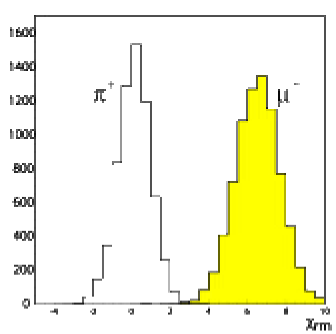
Tag kinematics outside $\pi\nu\nu$ box – in $K_{\pi 2}$ peak

Background Characterization

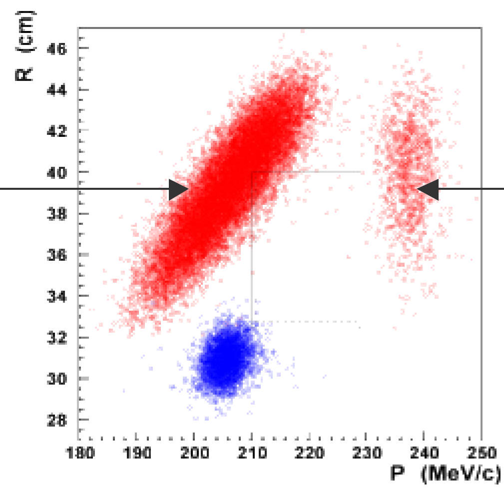
Background can be characterized using background functions

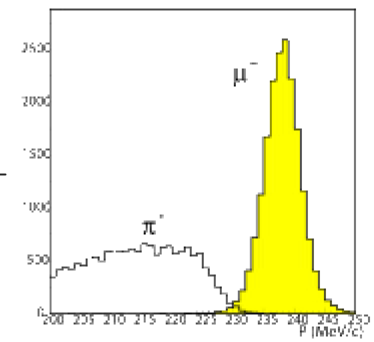
For muon backgrounds

- K_{m2}(tail) : **K_{m2}** but range is small due to interactions in RS.
- K_{mm}(band): multibody $K^+ \rightarrow m^+$ decay $(K^+ \rightarrow m^+ ng$, etc)

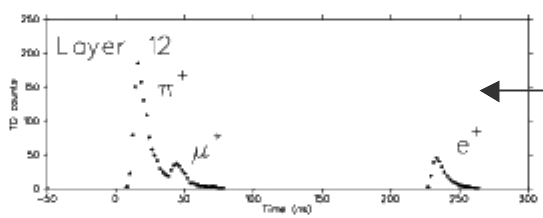


$$c_{rm} = \frac{R_{meas} - R_{exp}}{s_R}$$

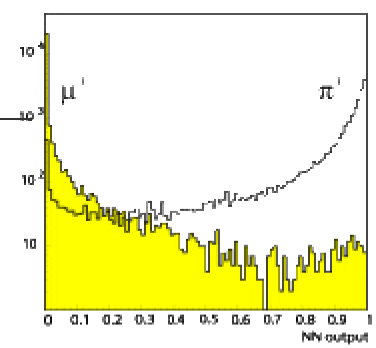




Momentum(P) for p and m



$p^+ \rightarrow m^+ \rightarrow e^+$ in the p^+ stopping counter



Neural net function for p and m

Changing cut position

⇓

Acceptance & background level at each point of parameter

⇓

Functions

Final Sensitivity and Background

- Sensitivity

	E787	E949	
N_K (10^{12})	5.9	1.8	**x 0.305**
Acceptance (%)	0.20 ± 0.02	0.22 ± 0.02	**x 1.1**
Sensitivity (10^{-10})	0.83	2.6	**x 0.336**

- Background
  - 30% larger acceptance, by enlarging the signal box to lower edge of E/P/R space, resulting in larger $K_{\pi 2}$ backgrounds

Source	E787	E949
$K_{\pi 2}$	0.032	0.216 ± 0.023
$K_{\mu 2}$	0.064	0.044 ± 0.005
$K_{\mu 2\gamma}$, …		0.024 ± 0.010
Beam	0.050	0.014 ± 0.003
Total	**0.14 ± 0.05**	**0.298 ± 0.026**

- All the cuts fixed and BG level estimated.
  Check the BG estimate with the data

Verify background prediction

- Loosen cuts and look in M x N times larger box
  - Two independent cuts for one background
    - For ex., Photon Veto or TD(NN function), and KINematics
- Compare prediction and observed # of events

$K\pi 2$	PV x KIN	10 x 10	20 x 20	20 x 50	50 x 50	50 x 100
	Observed	3	4	9	22	53
	Predicted	1.1 ± 0.18	4.9 ± 0.6	12.4 ± 1.3	31.1 ± 3.1	62.4 ± 5.6
$K\mu 2$	TD x KIN	10 x 10	20 x 20	50 x 50	80 x 50	120 x 50
	Observed	0	1	12	16	25
	Predicted	0.35 ± 0.03	1.4 ± 0.1	9.1 ± 0.6	14.5 ± 1.0	21.8 ± 1.5
$K\mu\nu\gamma$	TD x KIN	10 x 10	20 x 20	50 x 20	80 x 20	80 x 40
	Observed	1	1	4	5	11
	Predicted	0.31 ± 0.09	1.3 ± 0.4	3.2 ± 1.0	5.2 ± 2.2	10.4 ± 2.8

- Now, how to calculate the BR?

Likelihood method

- The signal region is divided into cells
  by binning parameter space (E, P, R, TD, photon veto…)
  - Once cuts are fixed, calculate BG level in each cell $\mathbf{b_i}$ inside box
  - Expected signal $\mathbf{S_i}$ from **BR** and calculated acceptance $\mathbf{A_i}$

    $\mathbf{S_i}$ = **BR** (as a free parameter) x $\mathbf{N_K}$ x $\mathbf{A_i}$
- Likelihood technique in small S_i, b_i (T.Junk, NIM **A434**, 435 (99))
  - Ratio of two Poisson probabilities (S+B or B only)
  - Estimator defined as

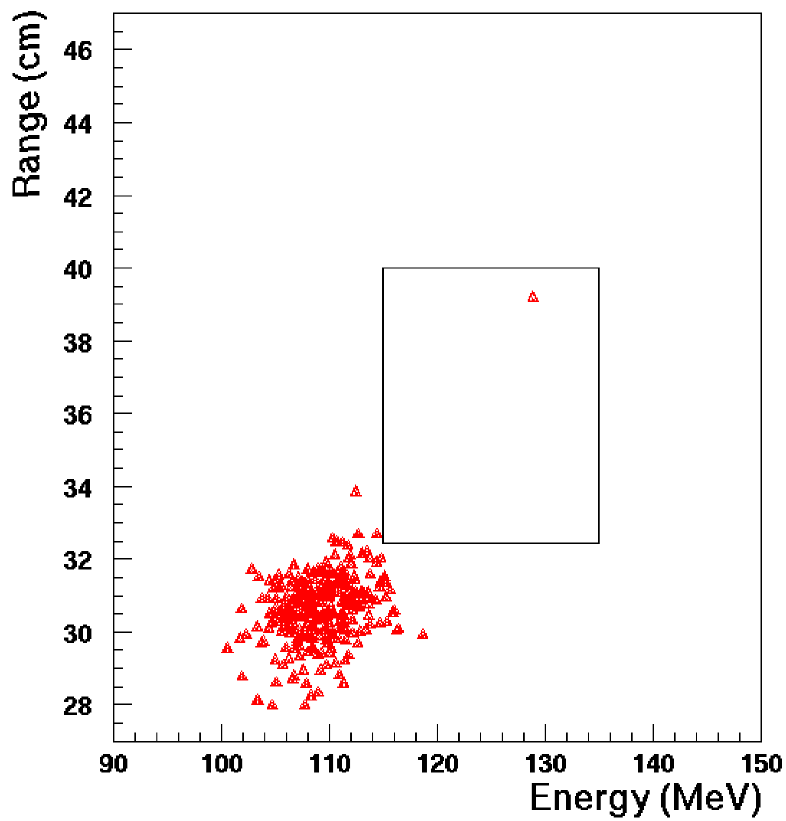
$$X(BR) = \prod_{i=1}^{n} \frac{\exp^{-(S_i+b_i)}(S_i+b_i)^{d_i}}{d_i!} \Bigg/ \frac{\exp^{-(b_i)}(b_i)^{d_i}}{d_i!} = \prod_{i=1}^{n} \exp^{-S_i}\left(1+\frac{S_i}{b_i}\right)^{d_i}$$

($\mathbf{d_i}$ = # of observed candidate in the cell)

➢ When **maximum X(BR)**, the central value of the **BR**

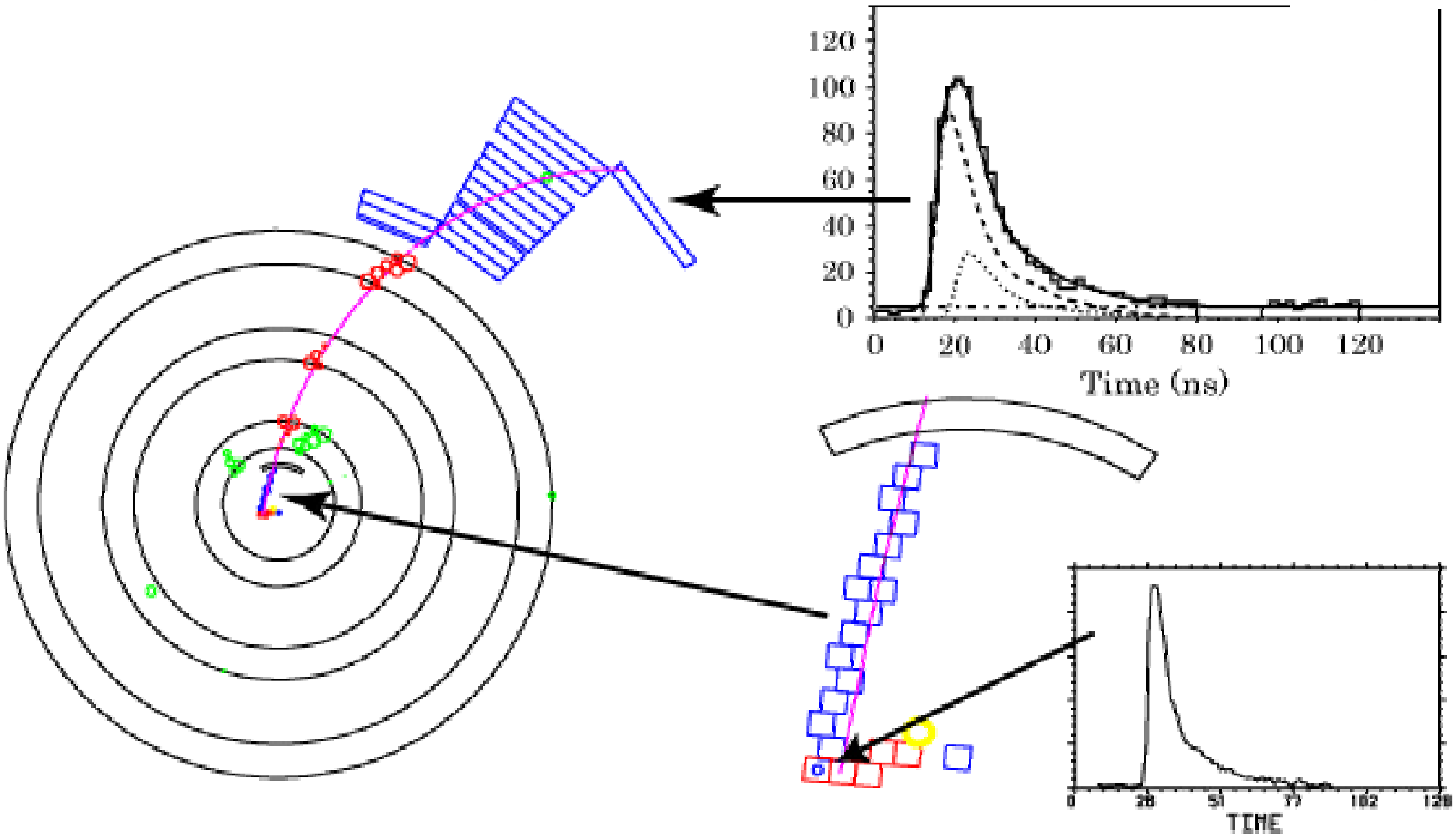
Open the Box

- Range vs. Energy after all other cuts are applied
- Box shows signal region
- Single candidate in the box



Details	
Momentum (MeV/c)	227.3
Range (cm)	39.2
Energy (MeV)	128.9
$K^+ \rightarrow \pi+$ decay time (ns)	4.3
$\pi^+ \rightarrow \mu^+$ decay time (ns)	6.2
$\mu^+ \rightarrow e^+$ decay time (ns)	1370

The 3rd $K^+ \rightarrow \pi^+ \nu\nu$ candidate



Branching ratio & Confidence level

- E949 result alone:

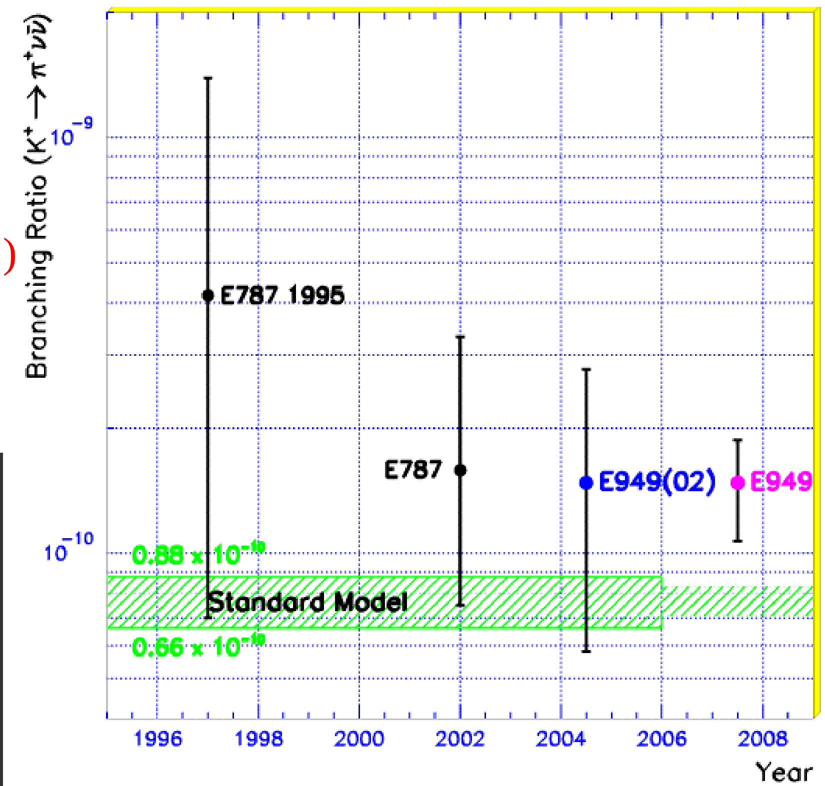
$$Br(K^+ \to p^+ n\bar{n}) = 0.96^{+4.09}_{-0.47} \times 10^{-10} \text{ (68\% CL)}$$

- Combine E787 and E949 results

$$Br(K^+ \to p^+ n\bar{n}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$ (68% CL)

PRL **93**, 031801 (2004)

	E787		E949
N_K (10^{12})	5.9		1.8
Candidate	E787A	E787C	E949A
S_i / b_i	50	7	0.9
$W_i=S_i/(S_i+b_i)$	0.98	0.88	0.48
BG Prob.	0.006	0.02	0.07



E949(02) = combined E787&E949.

E949 projection with full running period.

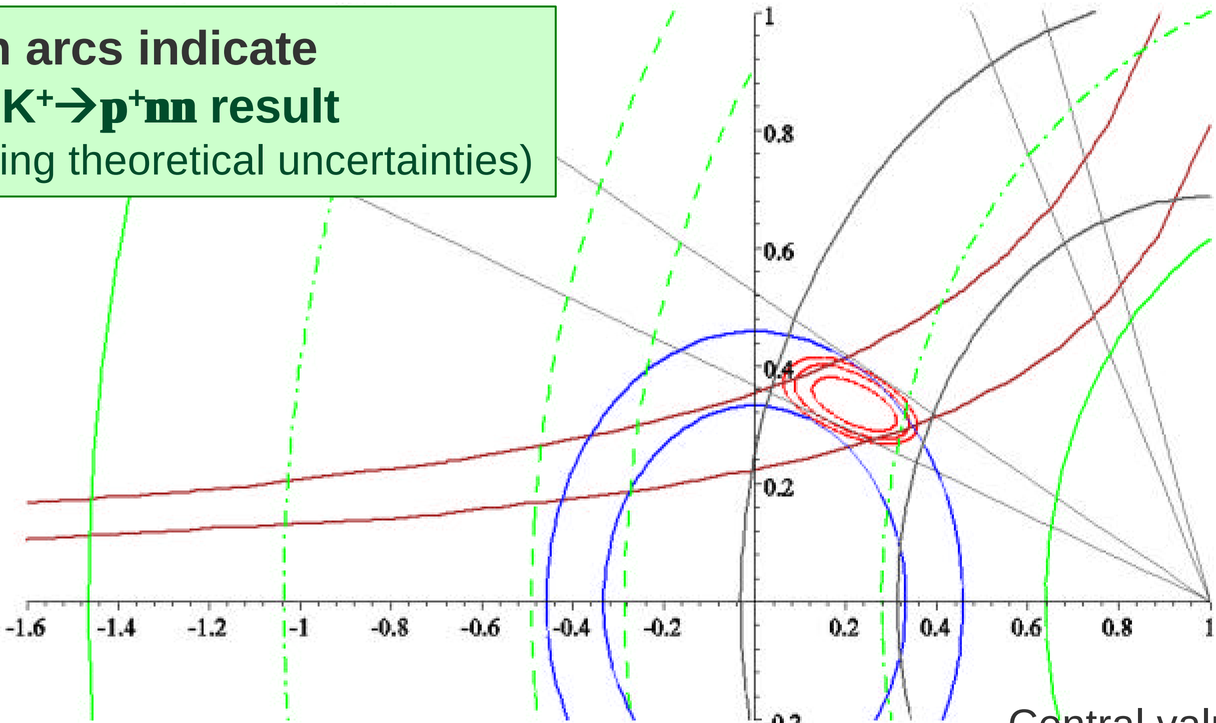
(~60 weeks)

Impact on Unitary Triangle

- Contour in ρ-η plane

courtesy of G. Isidori

Green arcs indicate
this $K^+ \rightarrow p^+$nn result
(including theoretical uncertainties)



Central value

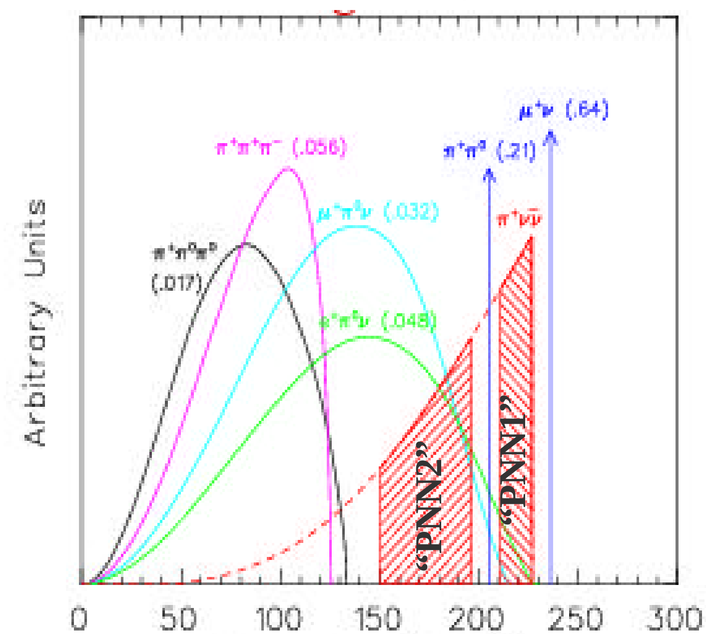
68% interval

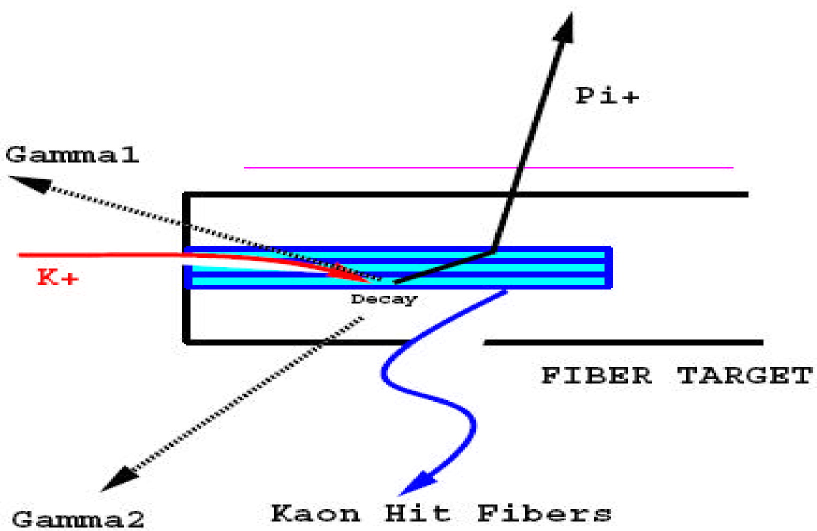
90% interval

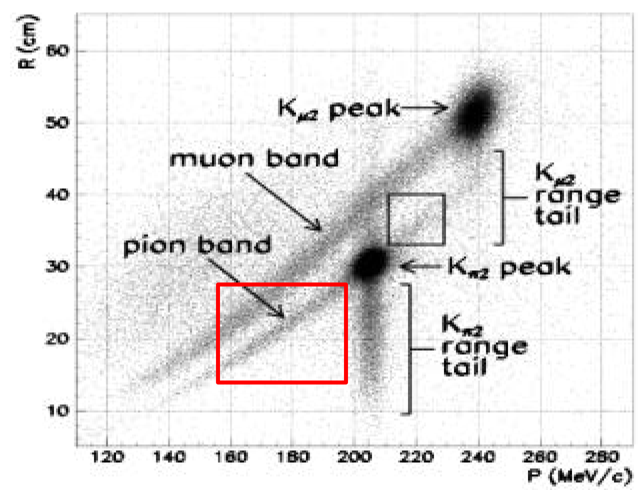
Central value
off the “SM”
→ **Need more data!!**

PNN2 analysis

- More phase space than pnn1
- Less loss from π^+N interactions
- Probe $K^+ \to \pi^+ \nu\nu$ spectrum
  - Main background is $K^+ \to \pi^+ \pi^0$ with π^+ scatter in target – loss of R and P with photons aimed at weak part of detector







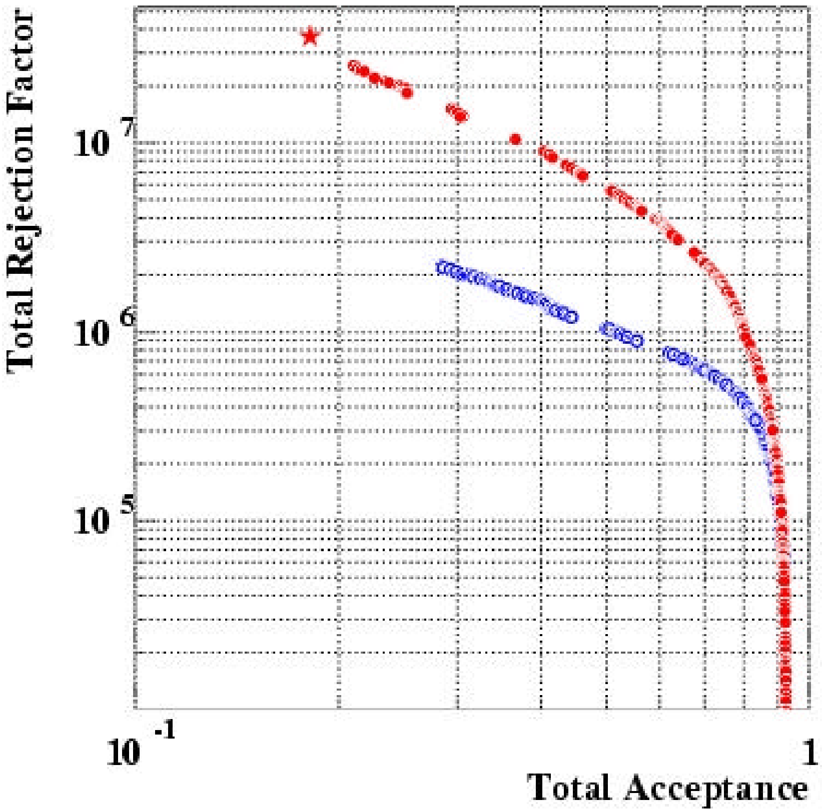
PNN2 analysis (2)

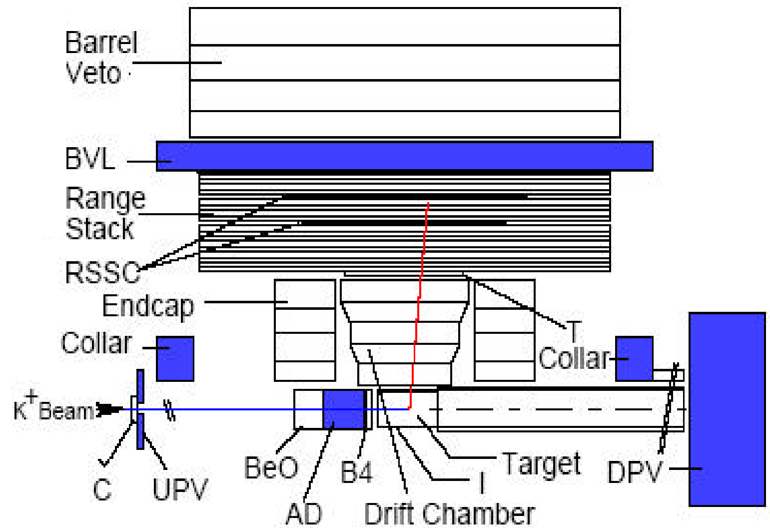
- *Goal: sensitivity equal to PNN1, s/b = 1* ⇒

  2 × acceptance and 5 × rejection

- Improved PV: new detectors at small angles

- Improved algorithms to identify ð⁺ scatters in target





PNN2 analysis (3)

E787 Result:

1996: PL **B537**, 211 (2002)
1997: PR **D70**, 037102 (2004)

- $140<p_p<195$ MeV/c
- 1 candidate event
- Expected background of 1.22 +/- 0.24 events
- $BR(K^+ \rightarrow \pi^+ \nu \nu) < 22 \times 10^{-10}$
- Background limited, with S/N<0.2

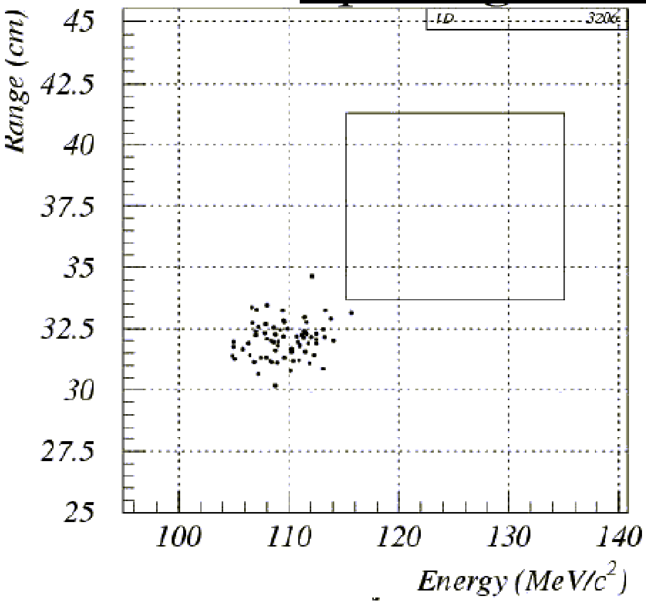
E787 Data:

- E949 data is being worked on now – improved photon veto rejection will improve the limit and may allow observation of $K^+ \rightarrow \pi^+ \nu \nu$ signal.

Other Physics

$K^+ \rightarrow \pi^+ \gamma\gamma$ (and $K^+ \rightarrow \pi^+ \gamma$)

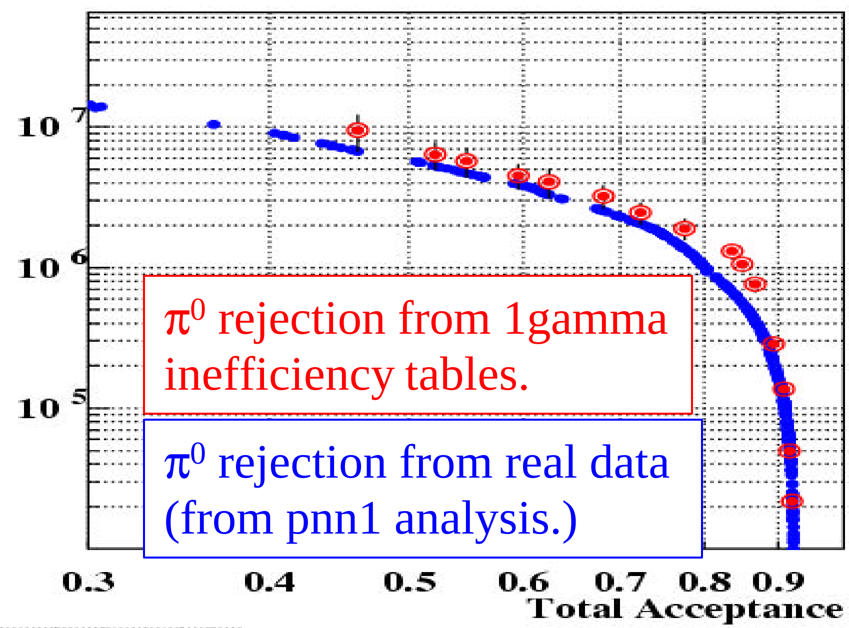
Opening-the-Box



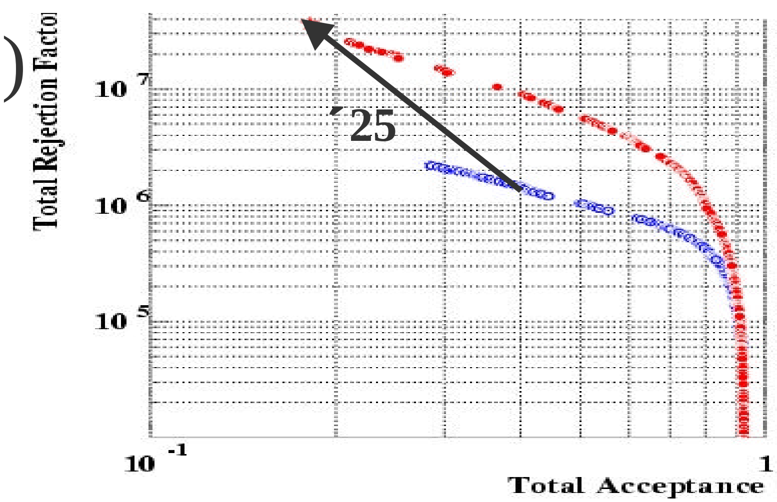
- Range(cm) and Energy(MeV) plot after all cuts imposed.
- Solid line : search region.
- No candidate found.
- Cluster near E=110MeV : un-rejected Kpi2.

11/6/2004 Mini-Workshop on Kaon Experiments and Detectors@Mikata 21

$\pi^0 \rightarrow \nu\nu$ (and $\pi^0 \rightarrow \gamma\nu\nu$)



$K^+ \rightarrow \pi^+ \nu\nu$ (pnn2)



..and from E787:

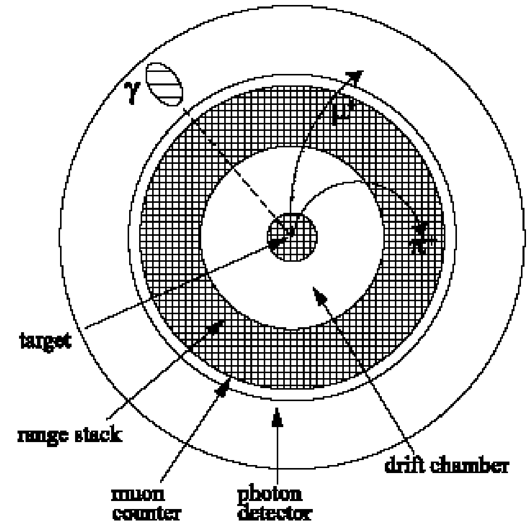
1. $K^+ \rightarrow \pi^+ \pi^0 \gamma$
2. $K^+ \rightarrow \mu^+ \pi^0 \nu \gamma$

Next steps for $K^+ \to \pi^+ \nu\nu$

- E949 at BNL
- L-04 at JPARC
- P940 at FNAL
- NA48-3 at CERN

$K^+ \rightarrow \pi^+ \nu\nu$ at JPARC

Early design based on E949. New design is being worked on.



JPARC L-04

(http://kaon.kek.jp/~kpwg)

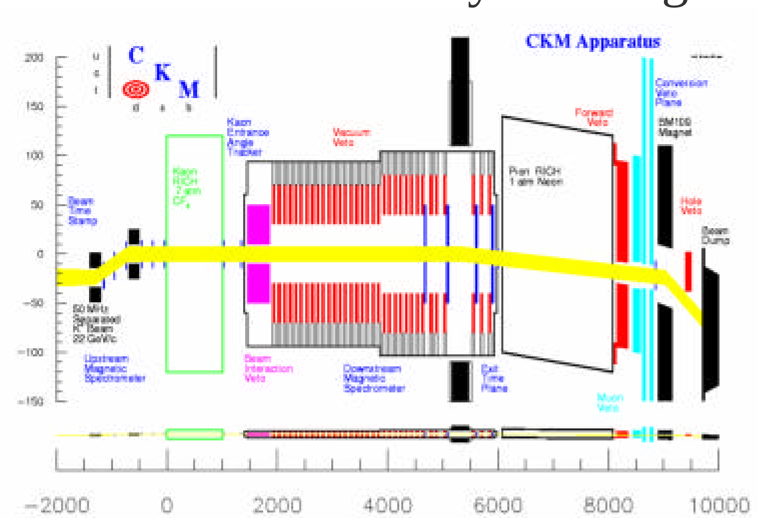
Stopped K$^+$®p$^+$nn experiment at JPARC

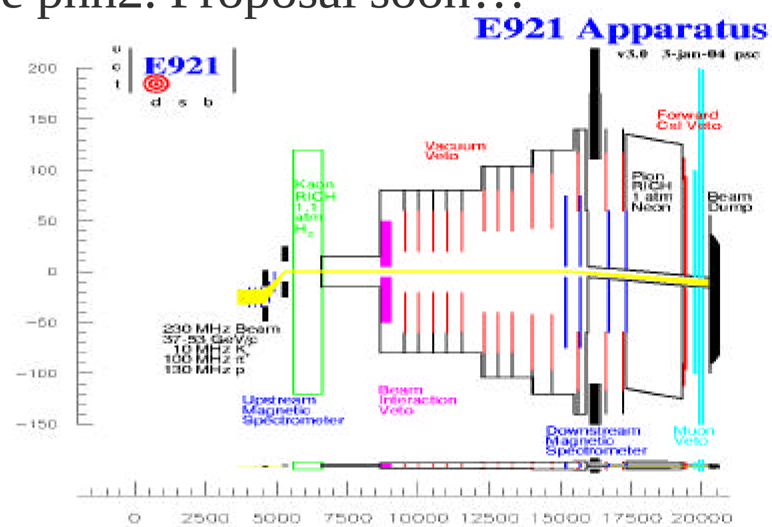
- Improvements relative to E949
  - running mode (x1.9)
    - Stopping fraction (x1.5)
    - Duty Factor (x0.83)
    - Hours (x1.5 = 3 years)
  - New Detector (x2.0)
  - Re-optimization (x1.5)
    - TD electron cut (x1.2)
    - Brighter, better E resolution (x1.2)
    - pipeline trigger (x1.1)

Goals: 50 SM events with S/N=5

$K^+ \rightarrow \pi^+ \nu\nu$ at FNAL

- **CKM:** approved by FNAL on 6/28/2001 to observe 100 SM events with S/N<10% in a separated 22 GeV/c K^+ beam. (http://www.fnal.gov/projects/ckm/documentation/public/proposal/proposal.html)
- P5 stops CKM - Oct 2003 *"CKM is an elegant world class experiment* which *based on present budgetary models should not proceed."*
- **P940**: Adapt to an unseparated 37-53 GeV/c beam in KTeV hall
  - 230MHz beam 4% K^+, 30 MHz/cm^2 μMegas to track beam, other detectors mostly unchanged. Utilize pnn2. Proposal soon…





CKM: separated K+ beam at 22 GeV/c P940: Un-separated beam at 37-53 GeV

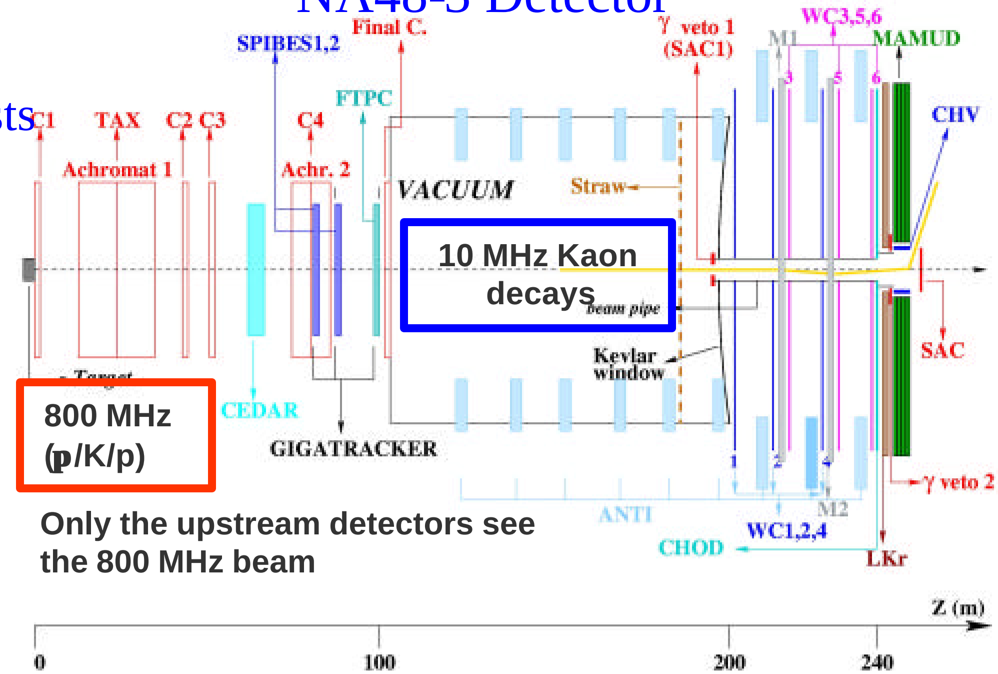
$K^+ \rightarrow \pi^+ \nu\nu$ at CERN

- LOI NA48-3 (http://www.cern.ch/NA48/NA48-3/Overview/LOI.pdf)
- Unseparated 70 GeV/c beam, 6% K^+
- Total flux of 800 MHz, with 40 MHz/cm^2
- Double magnet spectrometer

- Apparently favorable response from SPSC Villars meeting…
- 2004: R&D tracker, vacuum, straws
- 2005: complete R&D, proposal
- 2006-8: Construction, installation, beam tests
- 2009-10: Run

From A.Ceccucci

NA48-3 Detector



Question: What are the prospects for CERN to fund this?

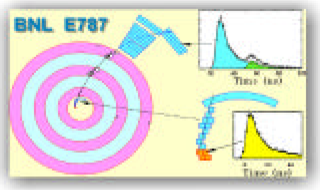
In-Flight vs. Stopped measurement of $K^+ \to \pi^+ \nu\nu$

In flight:

- Must measure K^+ momentum to recover rest-frame kinematics.
- Relatively large decay volume.
- Not possible to follow the $\pi^+ \to \mu^+ \to e^+$ decay chain.
- Unseparated technique must cope with much higher rates.
- No existence proof, such as E787/E949.
- Decay occurs in vacuum, no low-energy K^+A interactions, no complex energy loss mechanisms.
- Kinematics ***and backgrounds*** of Region-I and Region-II are similar with potentially higher total acceptance.
- High energy muons and photons from $K\mu 2$ and $K\pi 2$ may be easier to veto.
- Existing high performance in-flight experiments: BNL-871, BNL-E865, KTeV, NA48.

Comparison of experiments and proposals

	E787 Prop	E787 (as run)	E949 (run)	E949 Prop	CKM Prop	P940 EOI	JPARC LOI#4	NA48-3 LOI
$\|P_p\|$ (GeV/c)	25	25	22	25	120	120	30	400
P/spill	5 Tp	19 Tp	75 Tp	65 Tp	5 Tp	2 Tp	100 Tp	3 Tp
P/sec	2 Tp	9 Tp	30 Tp	10 Tp	1.7 Tp	0.7 Tp	23 Tp	0.2 Tp
DF	1s/2.4s 42%	2s/4.3s 48%	2.2s/5.4s 41%	4.1s/6.4s 64%	1s/3s 33%	1s/3s 33%	1.7s/4.4s 39%	4.8s/16.8s 29%
$\|P_K\|$	800 MeV/c	730 MeV/c	710 MeV/c	730 MeV/c	22 GeV/c	45 GeV/c	550 MeV/c	75 GeV/c
K/(K+p+$\bar{p}$)	0.25	0.8	0.7	0.8	0.7	0.04	0.75	0.06
K/sec (spill)	1.8 MHz	4 MHz	6 MHz	5 MHz	33 MHz	10 MHz	18 MHz	30 MHz
K/sec	0.8 MHz	1.8 MHz	2.4 MHz	3.1 MHz	11 MHz	3.3 MHz	7.0 MHz	9.0 MHz
Flux/Teff (spill)	7.2 MHz	5.6 MHz	8.4 MHz	6.7 MHz	50 MHz	250 MHz	25 MHz	800 MHz
F/(cm^2 ´ Teff)	0.1 MHz	0.07 MHz	0.11 MHz	0.09 MHz	0.25 MHz	30 MHz	0.3 MHz	40 MHz
`decay' factor	19%	23%	27%	26%	13%	17%	40%	9%
Sec/year	8×10^6	5×10^6	4×10^6	1×10^7	8×10^6	8×10^6	1×10^7	5×10^6
Year	1	4	1	2	2	2	3	2
Geom. Acc.	50%	27%	27%	27%	50%?	50%?	27%	50?
Acceptance	1.5%	0.2%	0.22%	0.3%	1.8%	2.1%	0.6%	10%
Pnn1(/yr)	1(1)	1.2(0.3)	0.4(0.4)	7(3)	95(47)	44(22)	50(17)	40(20)
Pnn2(/yr)		0.15(0.07)	0.4?	5(3)	130(65)	62(31)		40(20)



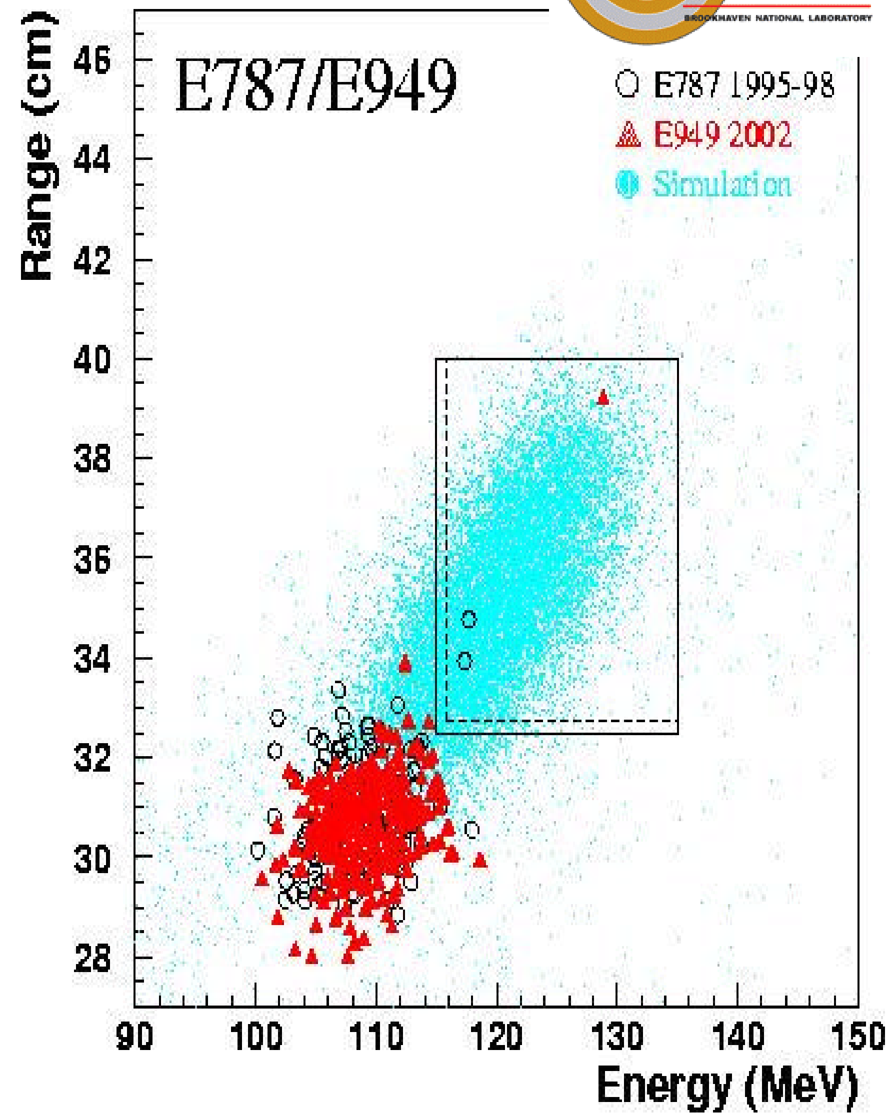
Summary & Outlook (1)

- E949 has observed a 3rd $K^+ \rightarrow \pi^+ \nu\nu$ event.

$B(K^+ \rightarrow \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$

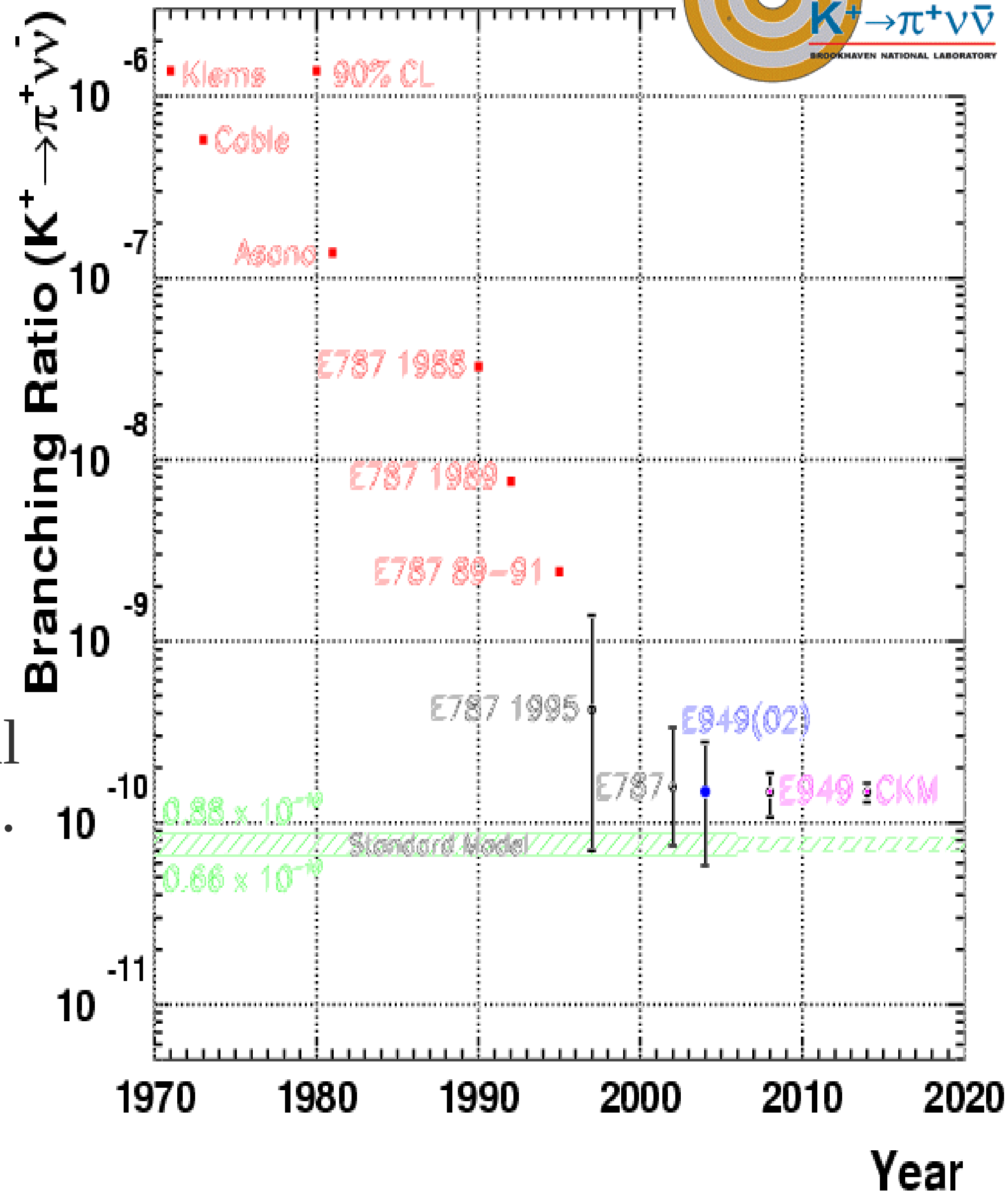
(SM: 0.8×10^{-10})

- PRL **93** (2004) 031801
- Detector and collaboration ready to complete experiment but DOE has not supplied funding for the running time that they approved.
  - Termination of AGS HEP ops. was a non-scientific decision imposed on the Office of Science.



Summary & Outlook (2)

- E787 discovered $K^+ \rightarrow \pi^+ \nu\nu$ and measured a BR twice the SM expectation
- BNL and FNAL developed a plan to fully exploit this kaon component of flavor physics with E949 and CKM.
- E949 was approved by DOE-HEP to exploit the investment in E787, the expertise, the proven detector and the minimal marginal cost to run with RHIC. CKM was approved by FNAL to take the next step and push the measurement of $K^+ \rightarrow \pi^+ \nu\nu$ to the limits of theory.

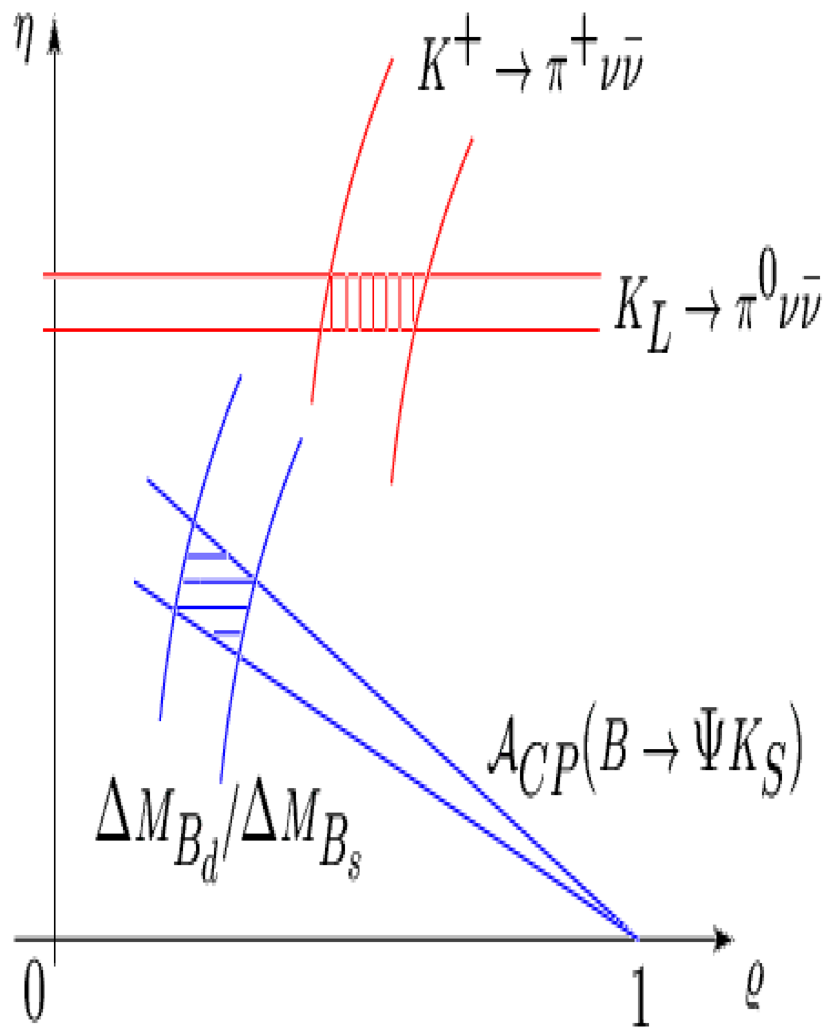


Summary & Outlook (3)

- E949 remains an approved but now un-funded DOE experiment.
- CKM appears to be dead.
- NSF has expressed interest in $K^+ \rightarrow \pi^+ \nu\nu$: a proposal to complete E949 has been awaiting RSVP management reorganization and RSVP construction funding.
- What about the longer term future: a high rate unseparated experiment at FNAL or CERN? or a stopped JPARC experiment?
- It is clear that $K^+ \rightarrow \pi^+ \nu\nu$ remains an incisive test of the flavor structure of our physical world, whether described by the SM or new physics and some combination of experiments should go forward!
- Two $K_L \rightarrow \pi^0 \nu\nu$ experiments are now on reasonably strong footing (E391a has data; KOPIO starting construction).
- Which national governments and labs are most likely to support a $K^+ \rightarrow \pi^+ \nu\nu$ experiment? Can the community unite behind such effort(s)?

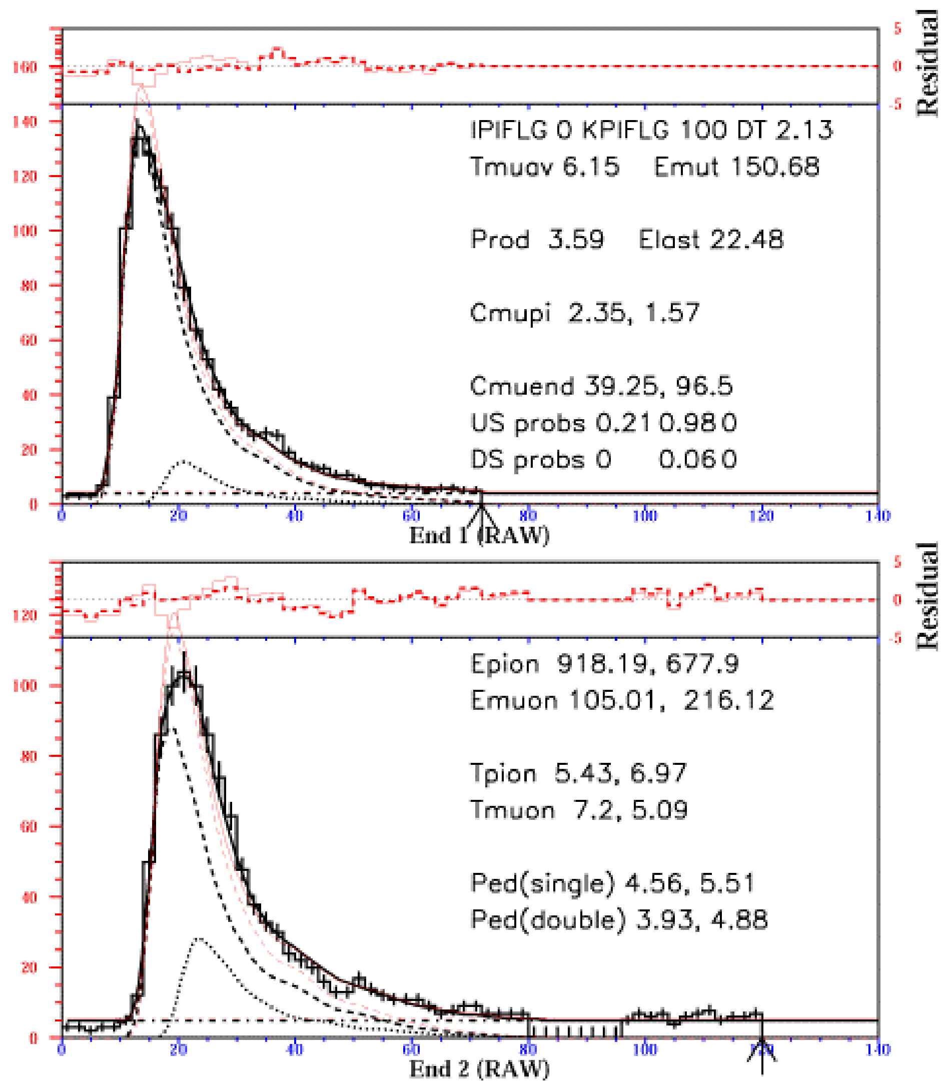
Summary & Outlook (4)

- E949 observed a 3rd $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ event – consistent with the SM prediction (and equally consistent with 3 times the SM). It is twice the expectation.
- Lower Phase space region accessible - results next year with similar sensitivity (≈double E949 sensitivity).
- Detector and collaboration ready to complete experiment but …?
- Together $K^+ \rightarrow \pi^+ \nu\nu$ and $K_L \rightarrow \pi^0 \nu\nu$ provide a unique opportunity for discovery of new physics. KOPIO (and E391) will be enhanced by a $K^+ \rightarrow \pi^+ \nu\nu$ experiment.



Backup

Pulse fitting in the π^+ stopping counter



TD properties of the candidate

- Plots with π^+ and μ^+ samples

  Arrows show the candidate event

Blue: π^+ (fitted $\pi \rightarrow \mu$ time<10ns)

Red : μ^+