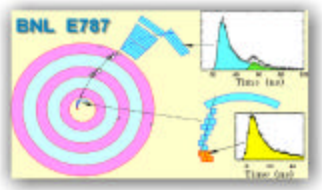


$K^+ \rightarrow \pi^+ \nu\nu$ Results: E787 & E949

Steve Kettell , BNL

May 26th, 2005

K-Rare Decays Workshop, LNF

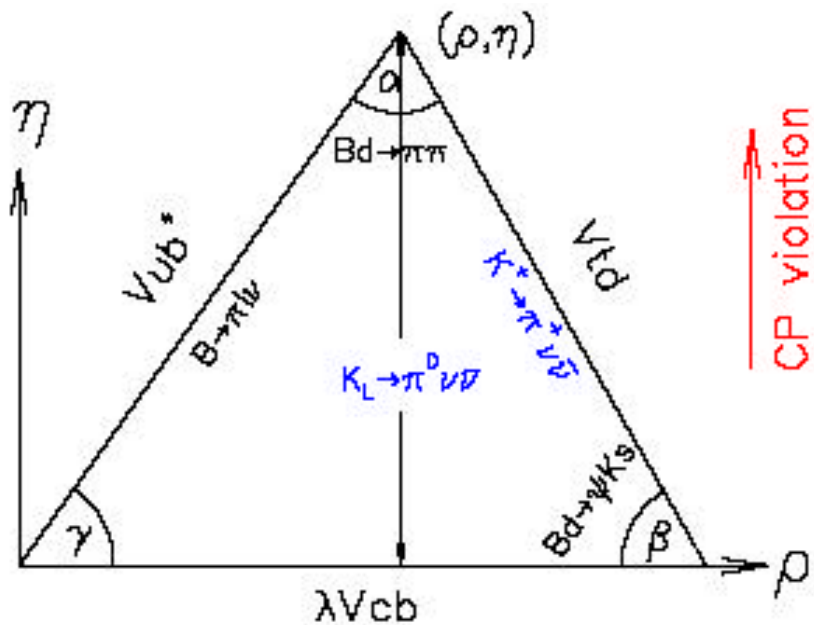
I. Overview of $K^+ \rightarrow \pi^+ \nu\nu$.

II. Details of E949.

III. Conclusions.

Motivation

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

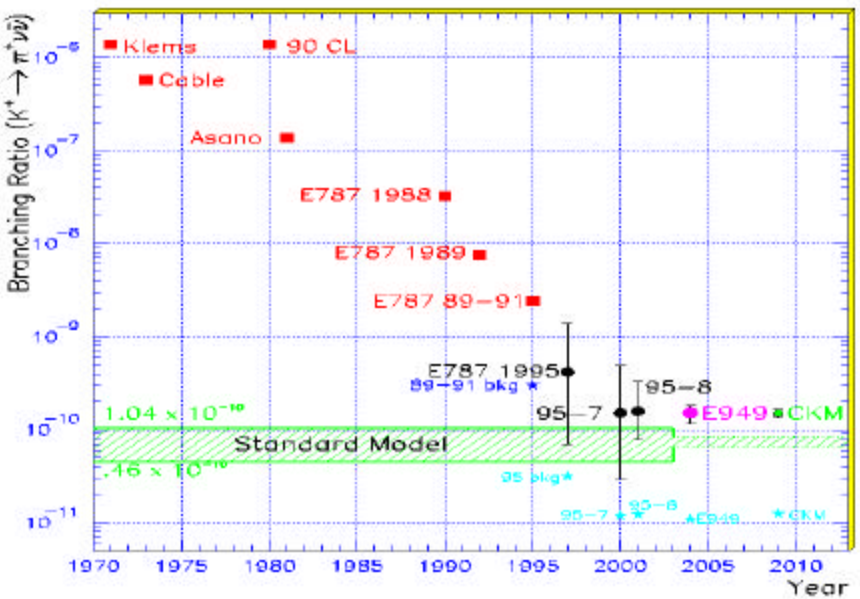


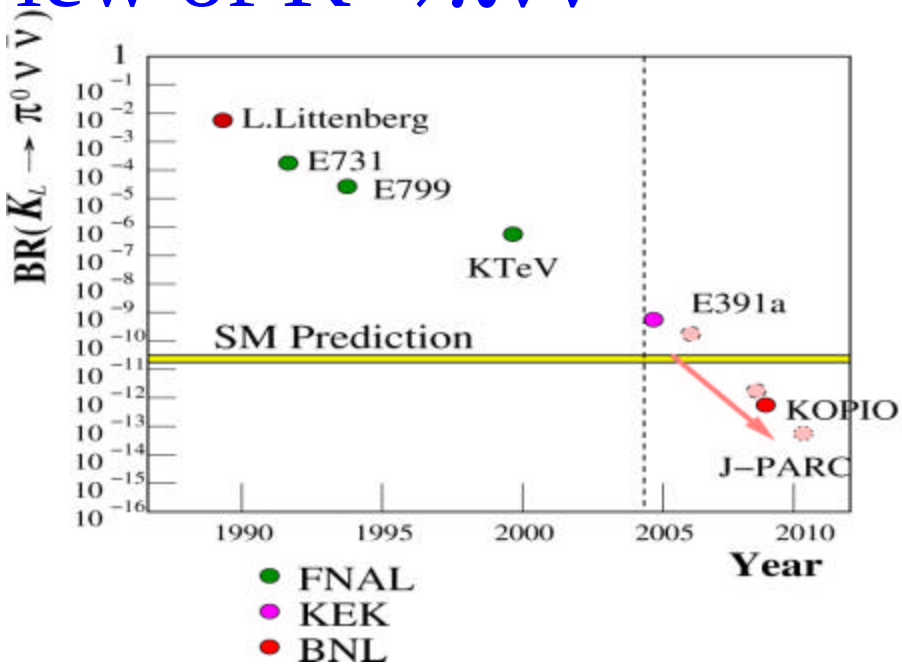
Four very clean processes

Process	Experiments
$B(K^+ \to \pi^+ \nu\bar{\nu})$	**E787/E949**,…?
$B(K^0 \to \pi^0 \nu\bar{\nu})$	E391, KOPIO
$A(B \to J/\psi K_s^0)$	BaBar, Belle
$\Delta M_{Bs}/\Delta M_{Bd}$	LHCb

Perhaps the most incisive test of the SM picture of CP violation is to verify $b_{yK}=b_{pnn}$ from $A(B_d \to J/\psi\ K_s^0)$ & $B(K_L \to \pi^0\nu\bar{\nu})/B(K^+ \to \pi^+\nu\bar{\nu})$

Worldwide Overview of $K \to \pi\nu\nu$



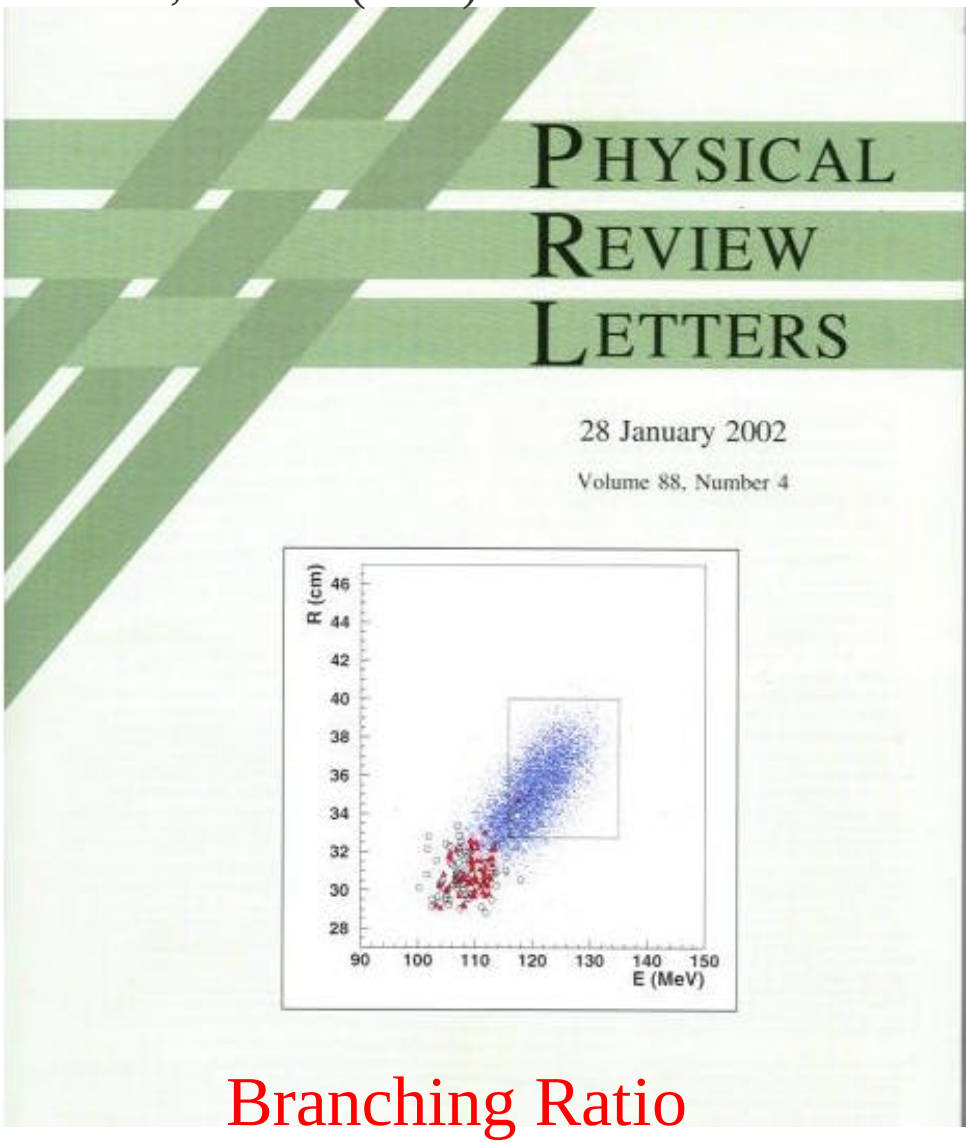


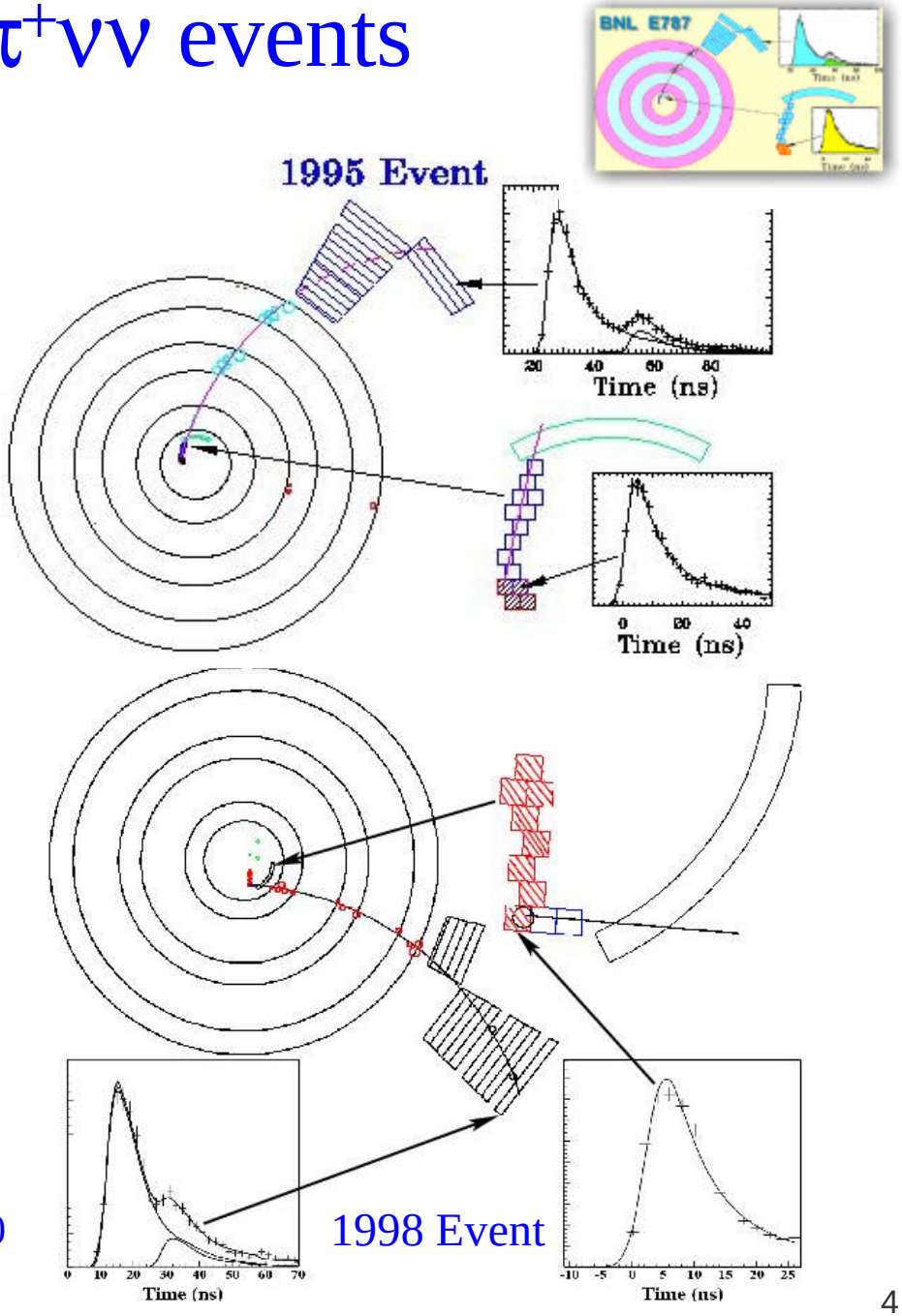
- E787: completed (1988-98); discovered two $K^+ \to \pi^+\nu\nu$ events (DAR)
- E949: 2002 run; approved but not funded for 50 more weeks…(DAR)
- CKM: FNAL scientific approval; P5 says no (separated DIF)
- P940: FNAL LOI for unseparated DIF (rejected: not enough protons)
- LOI's: JPARC L-04 (DAR) and 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 100 $K_L \to \pi^0\nu\nu$ events

PRL **88**, 041803 (2002)

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





Branching Ratio

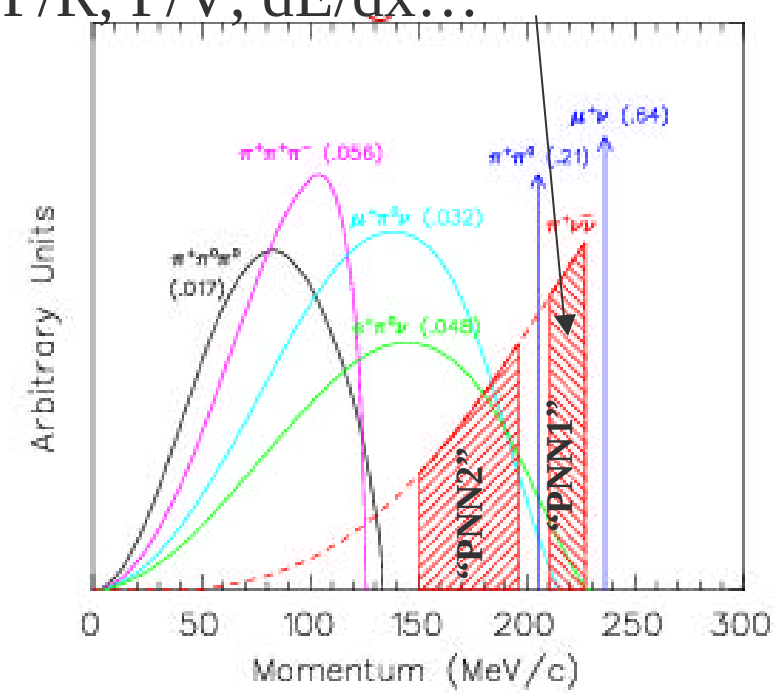
$$B(K^+ \rightarrow p^+ n\bar{n}) = 1.57 \pm^{1.75}_{0.82} \; x\; 10^{-10}$$

Steve Kettell, BNL

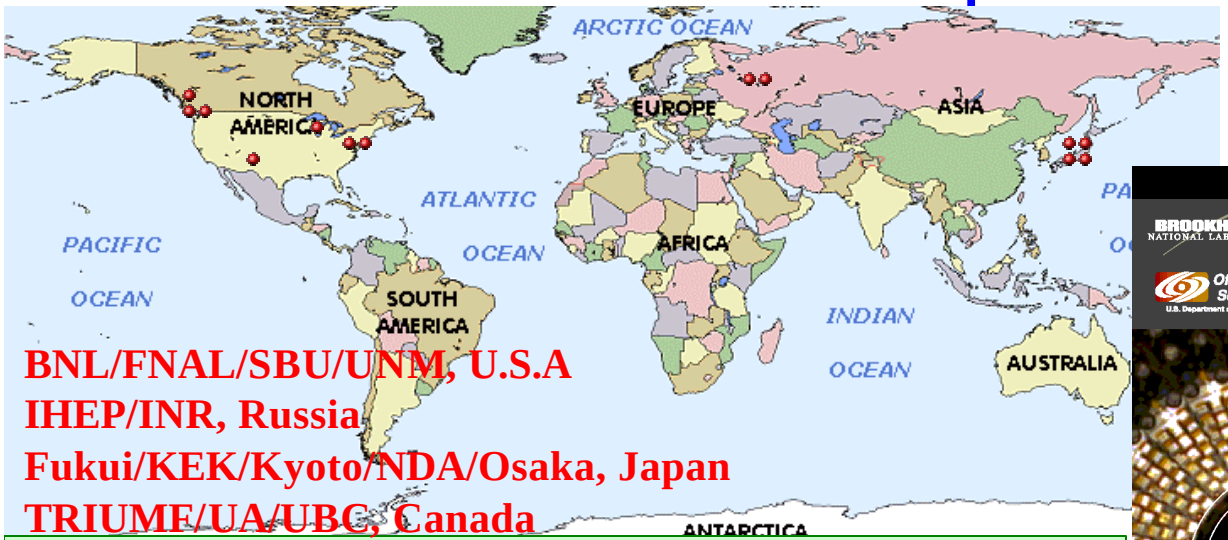
Outline of $K^+ \rightarrow \pi^+ \nu\nu$ Experimental Method

- **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)
    or Velocity (V) / Momentum (P) / Range (R)
  - PID: π-μ-e decay chain and/or P/R, P/V, dE/dx…
  - Hermetic veto detectors (γ)
- Major backgrounds
  - $K^+ \rightarrow \mu^+\nu$ (Br=63%)
    - Kinematics (monochromatic)
    - PID: π^+/μ^+
  - $K^+ \rightarrow \pi^+\pi^0$ (Br=21%)
    - Kinematics (monochromatic)
    - Photon veto
  - Scattered beam particles
    - Timing
    - PID: K^+/π^+

Primary signal region



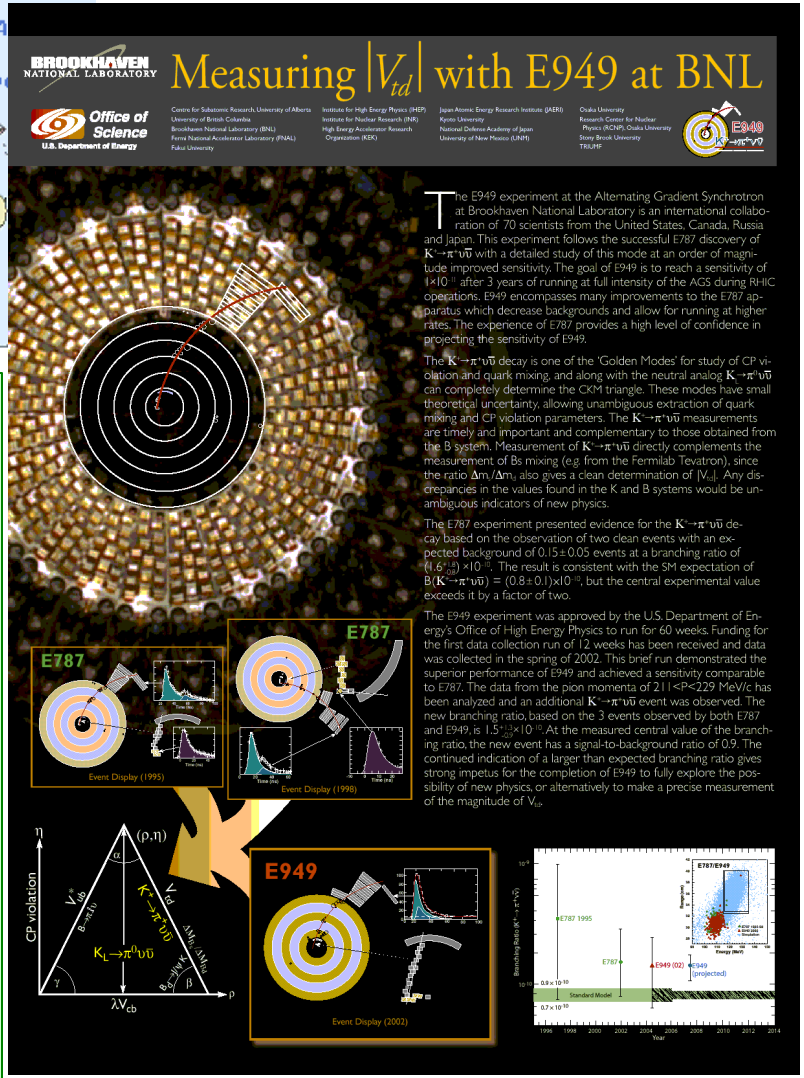
E949 Experiment



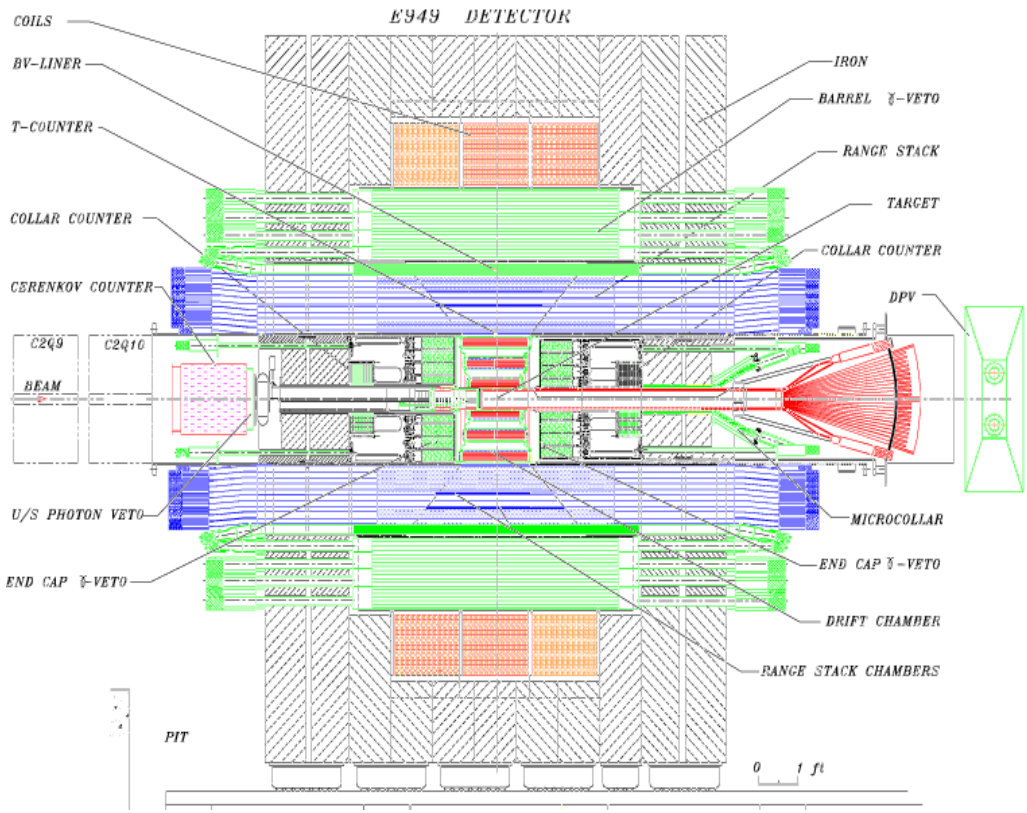
BNL/FNAL/SBU/UNM, U.S.A
IHEP/INR, Russia
Fukui/KEK/Kyoto/NDA/Osaka, Japan
TRIUMF/UA/UBC, Canada

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.



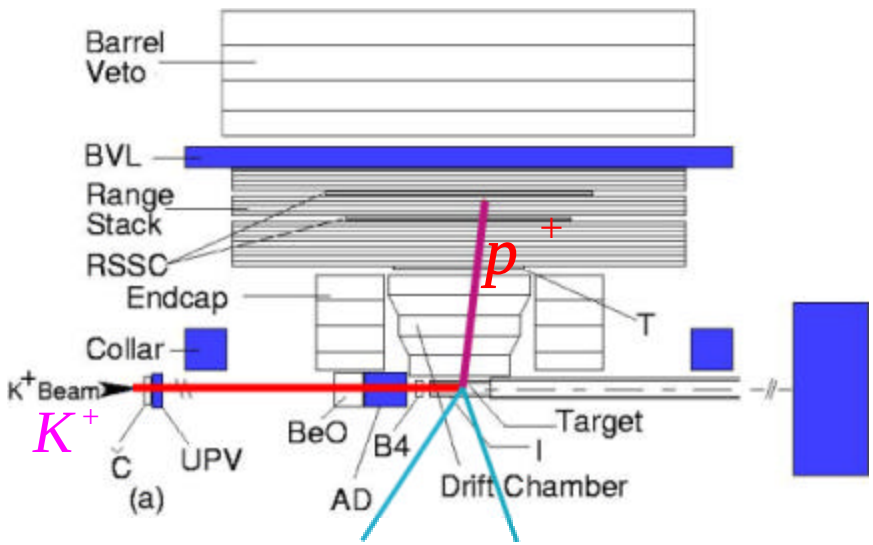
E949 Detector (1): Overview



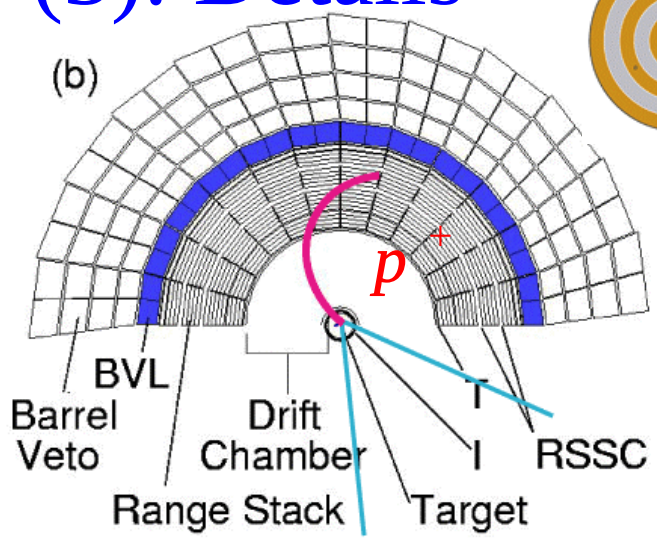
E949 Detector (2): Upgrades

- 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)

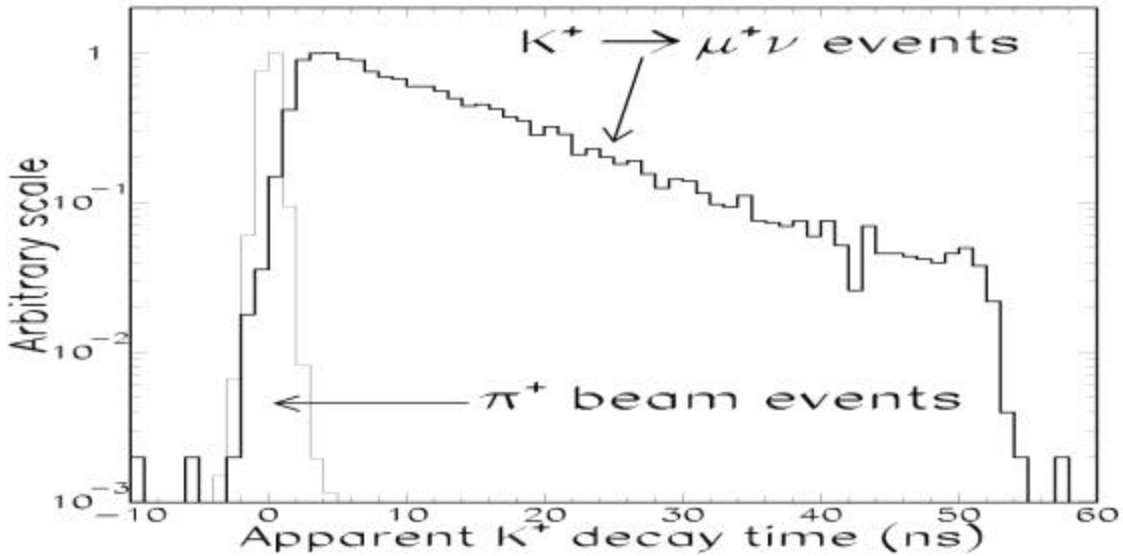
- 700 MeV/c K^+ beam (80%)
- Active target (scintillation fibers) to stop K^+
- Wait at least 2ns for K^+ decay
- Drift chamber to measure π^+ momentum
- 19 layers of scintillator, Range Stack (RS) to measure E and R
- Stop π^+ in RS, waveform digitizer to record π^+-μ^+-e^+ decay chain

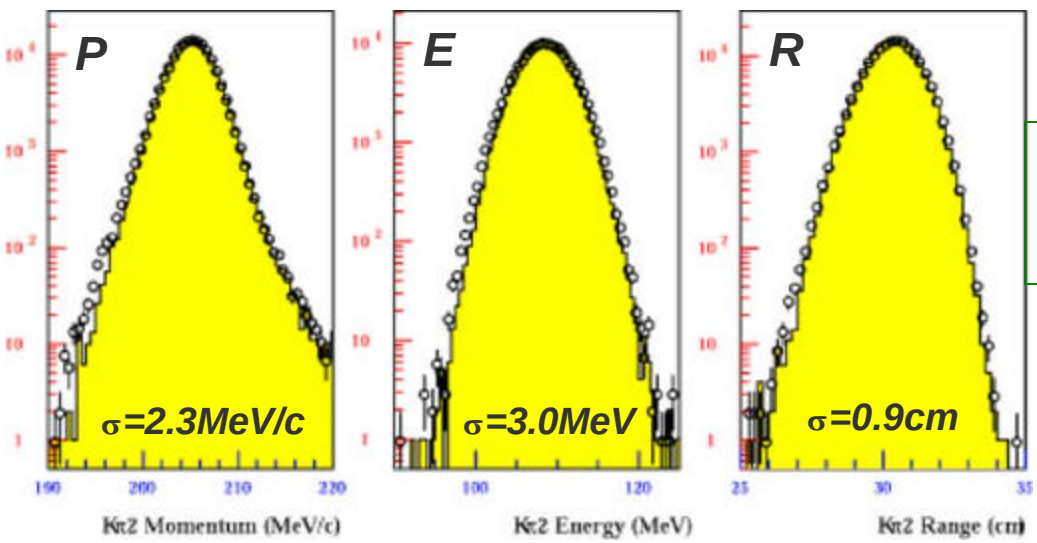
Renew inner 5 layers!
Equip gain monitor!

New!

- Veto photons, charged tracks over 4π (BV/BVL/Endcap/…)

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





K_{p2} momentum, energy and range

E949 (yellow histogram) vs. E787 (circle)

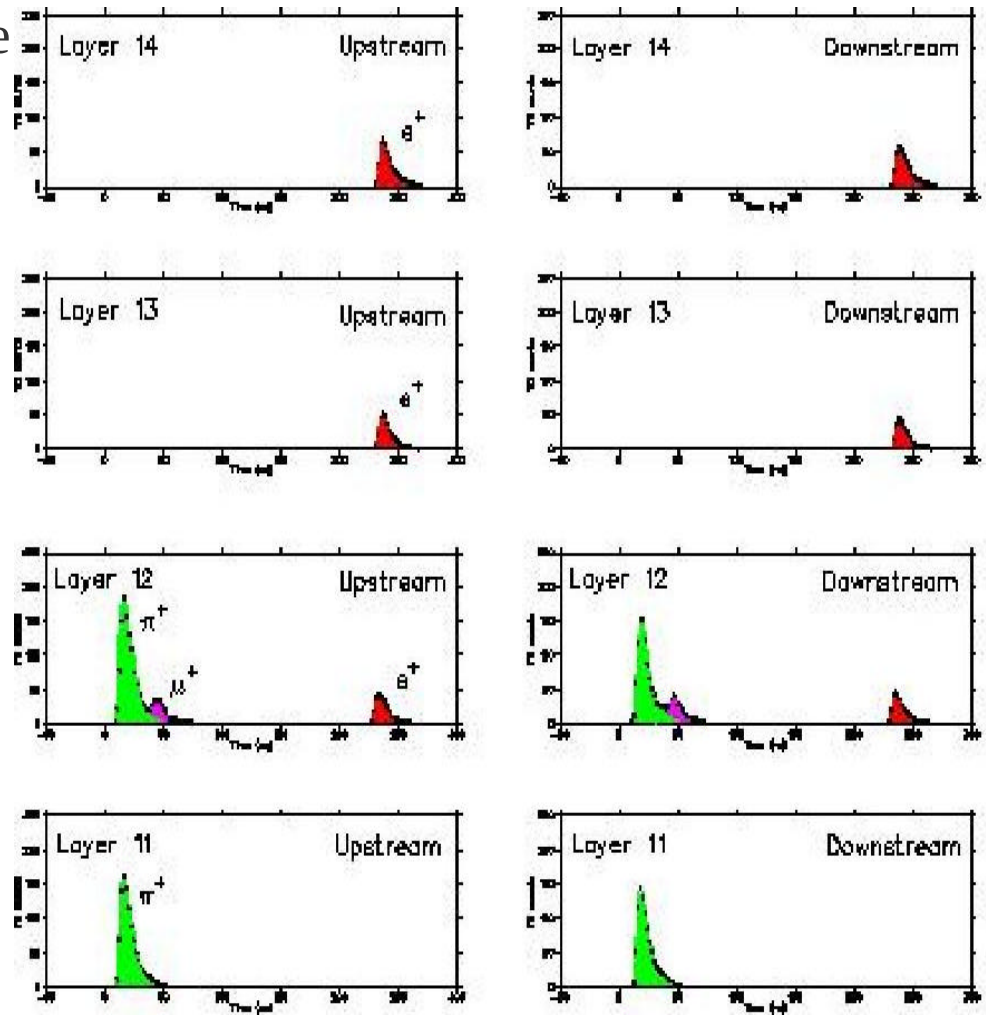
Same or even better resolution in 2 x higher rate environment

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

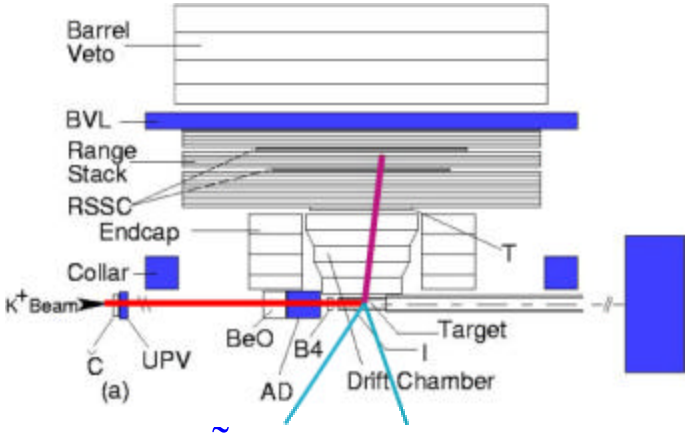
- Transient Digitizers (**TD**'s) sample pulse height every 2ns for 2μs.
- π^+ stops in range stack scintillator (2cm/layer)
- $\pi^+ \rightarrow \mu^+ \nu$, E_μ=4.1 MeV, R_μ =1mm, τ_π=26ns
- $\mu^+ \rightarrow e^+ \nu \nu$, E_e<53 MeV, τ_μ =2.2 μ s

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

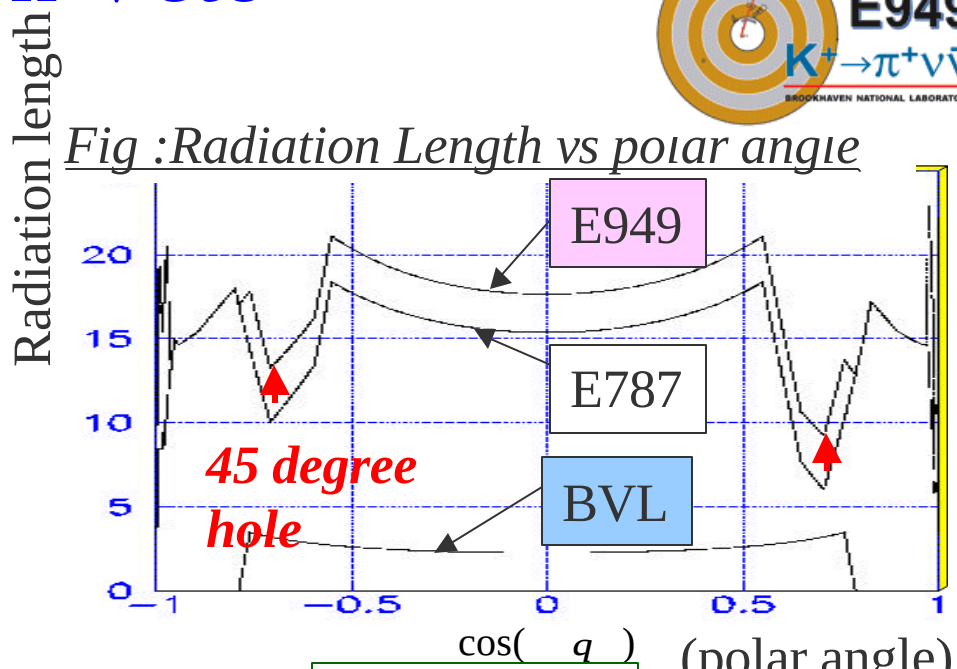
π^+ comes from inner layers and stops in Layer 12, where it decays to a μ^+, which then decays to an e^+ and propagates out to Layer 14.



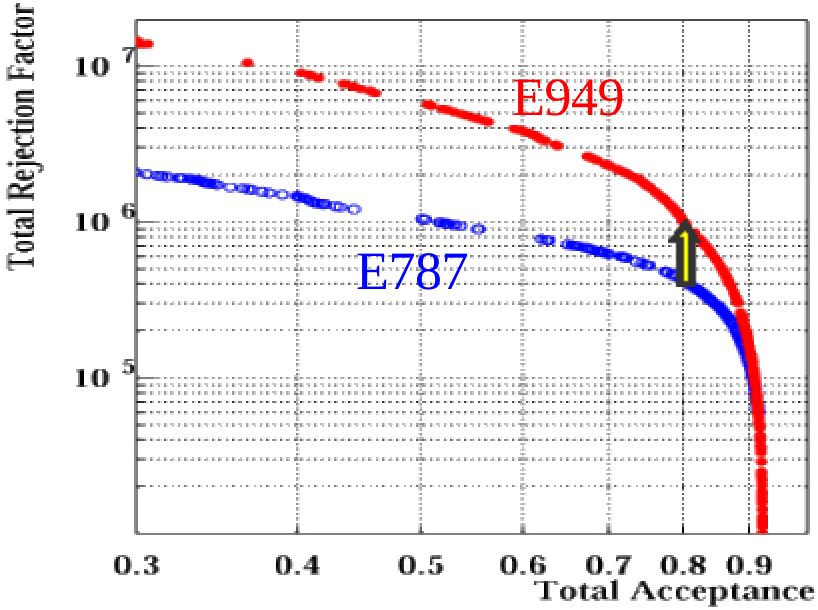
Photon Veto



New ã detectors in blue.



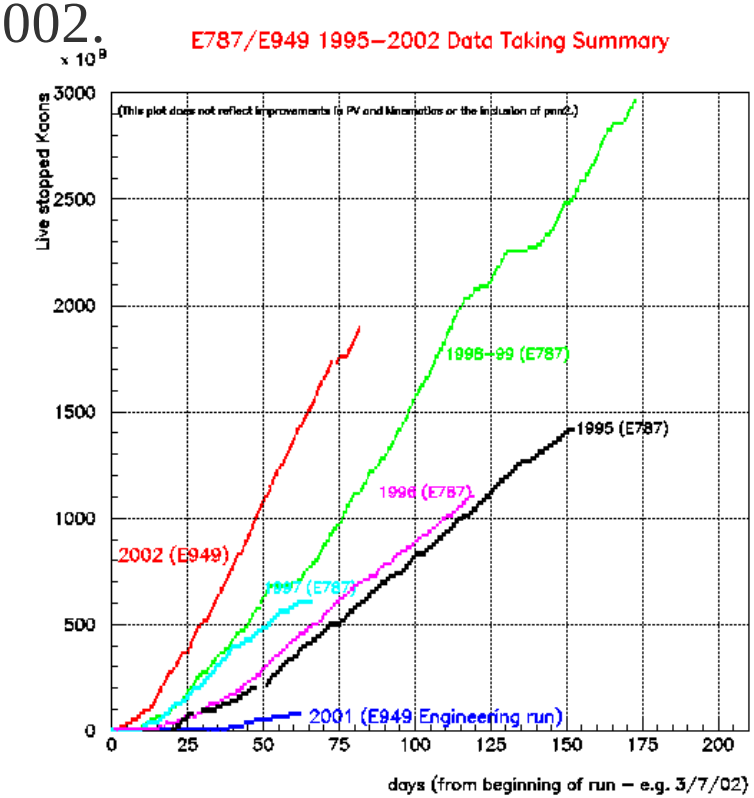
ð^0 rejection



- 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 $N_K=5.9\times10^{12}$ in 81 weeks over 5 years.
- E949 proposed $N_K=18\times10^{12}$ in 60 weeks over 3 years.
- E949 collected $N_K=1.8\times10^{12}$ 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 $K^+ \rightarrow \pi^+\pi^0$ region (PNN1)

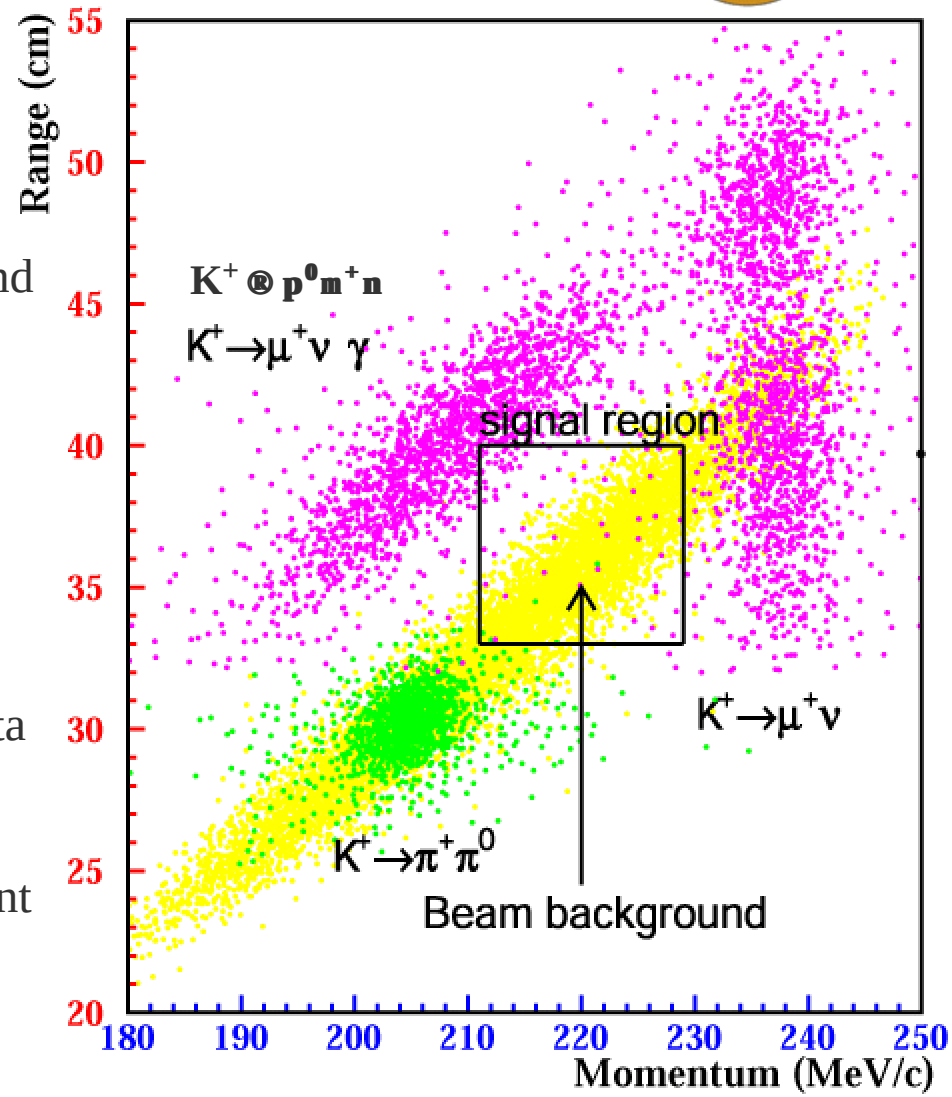
Background sources

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

- $K^+ \rightarrow \pi^+\pi^0$
- Muon background ($K^+ \rightarrow \mu^+\nu(\gamma)$,...)
- Beam background

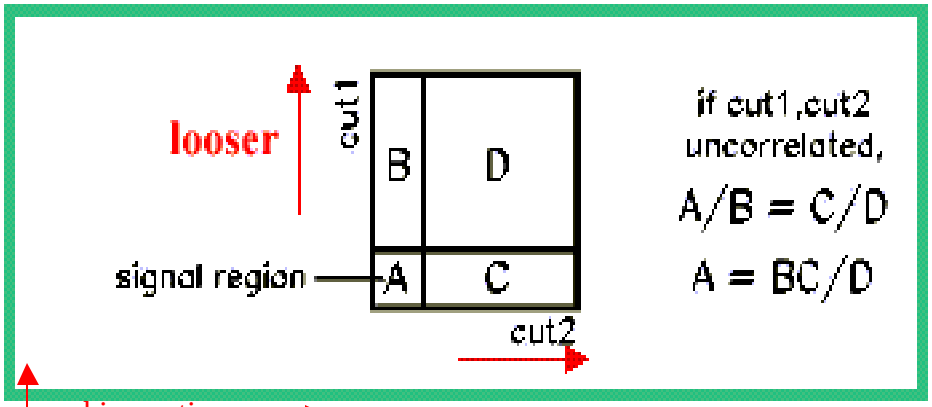
Analysis Strategy

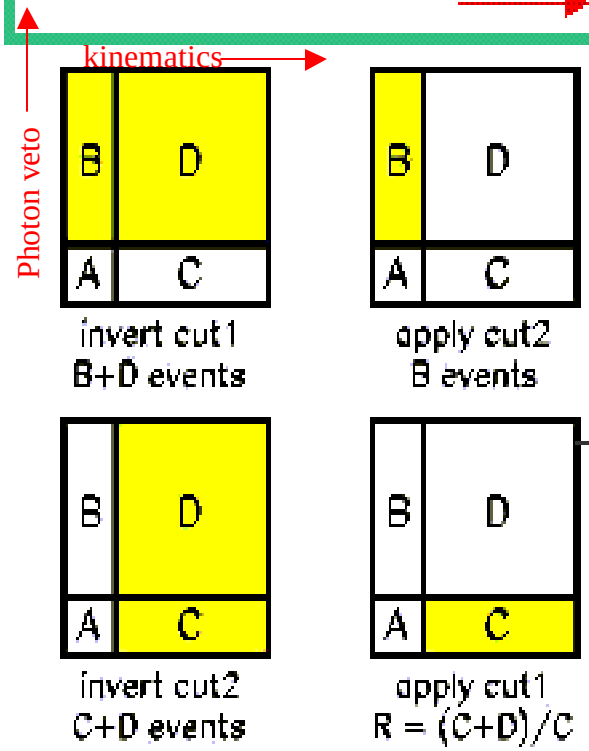
- Blind Analysis
- Measure Background level with real data
- To avoid bias,
  1/3 of data $\Rightarrow$ cut development
  2/3 of data $\Rightarrow$ background measurement
- Characterize backgrounds using background functions
- Likelihood Analysis

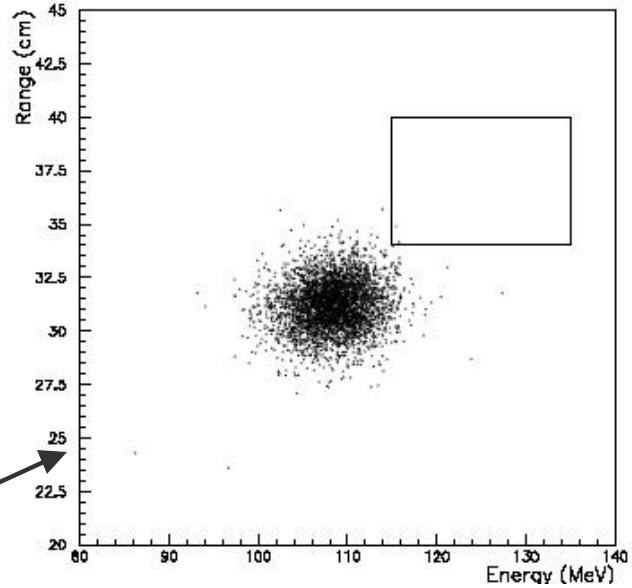


Calculation of backgrounds

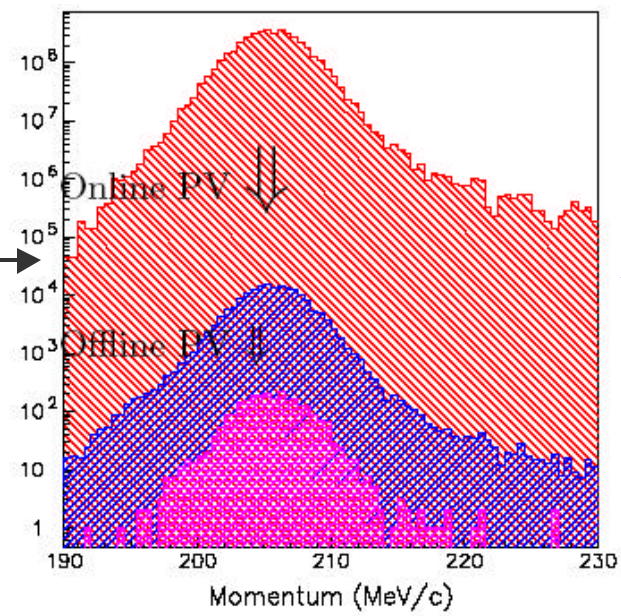
Illustration of Bifurcation Method







Tag with γ



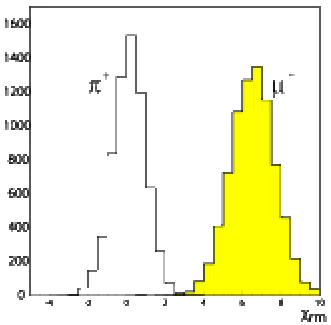
Tag kinematics outside πνν box – in $K_{\pi 2}$ peak

Background Characterization

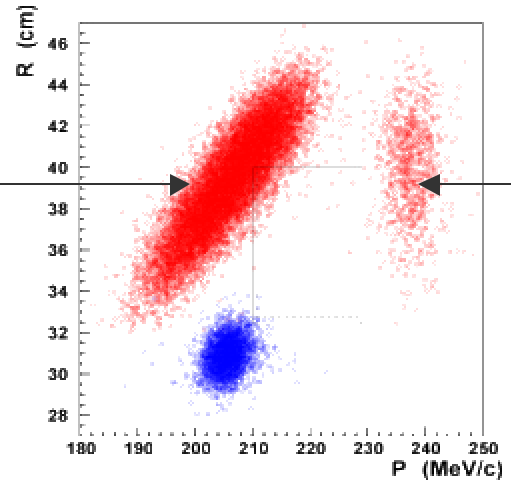
Background can be characterized using background functions

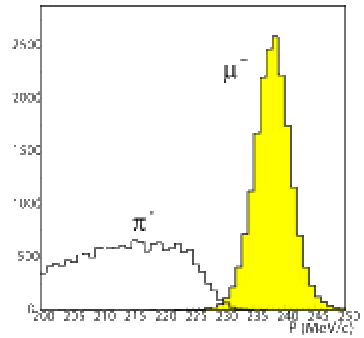
For muon backgrounds

- K_{m2}(tail) : $K_{\mu 2}$ but range is small due to interactions in RS.
- K_{mm}(band): multibody $K^+ \rightarrow m^+$ decay ($K^+ \rightarrow m^+ \nu g$, etc)

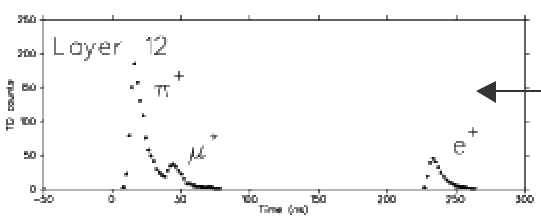


$$c_{rm} = \frac{R_{meas} - R_{exp}}{s_R}$$

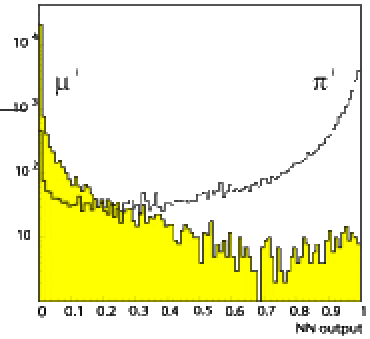




Momentum(P) for p and m



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



Neural net function for π and μ

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

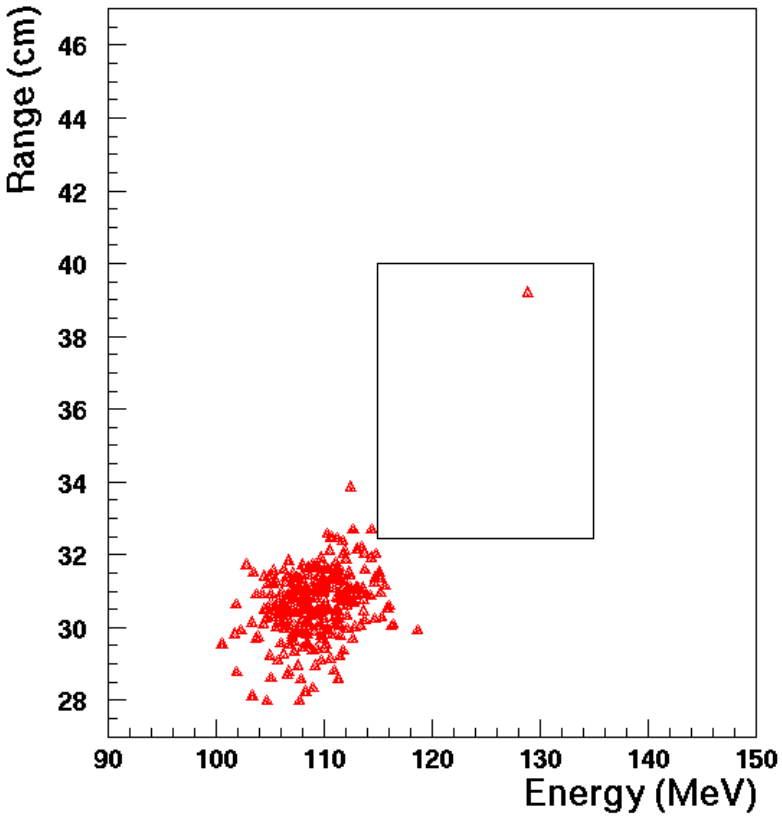
Verify background prediction

- 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

Kπ2	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
Kμ2	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
Kμνγ	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

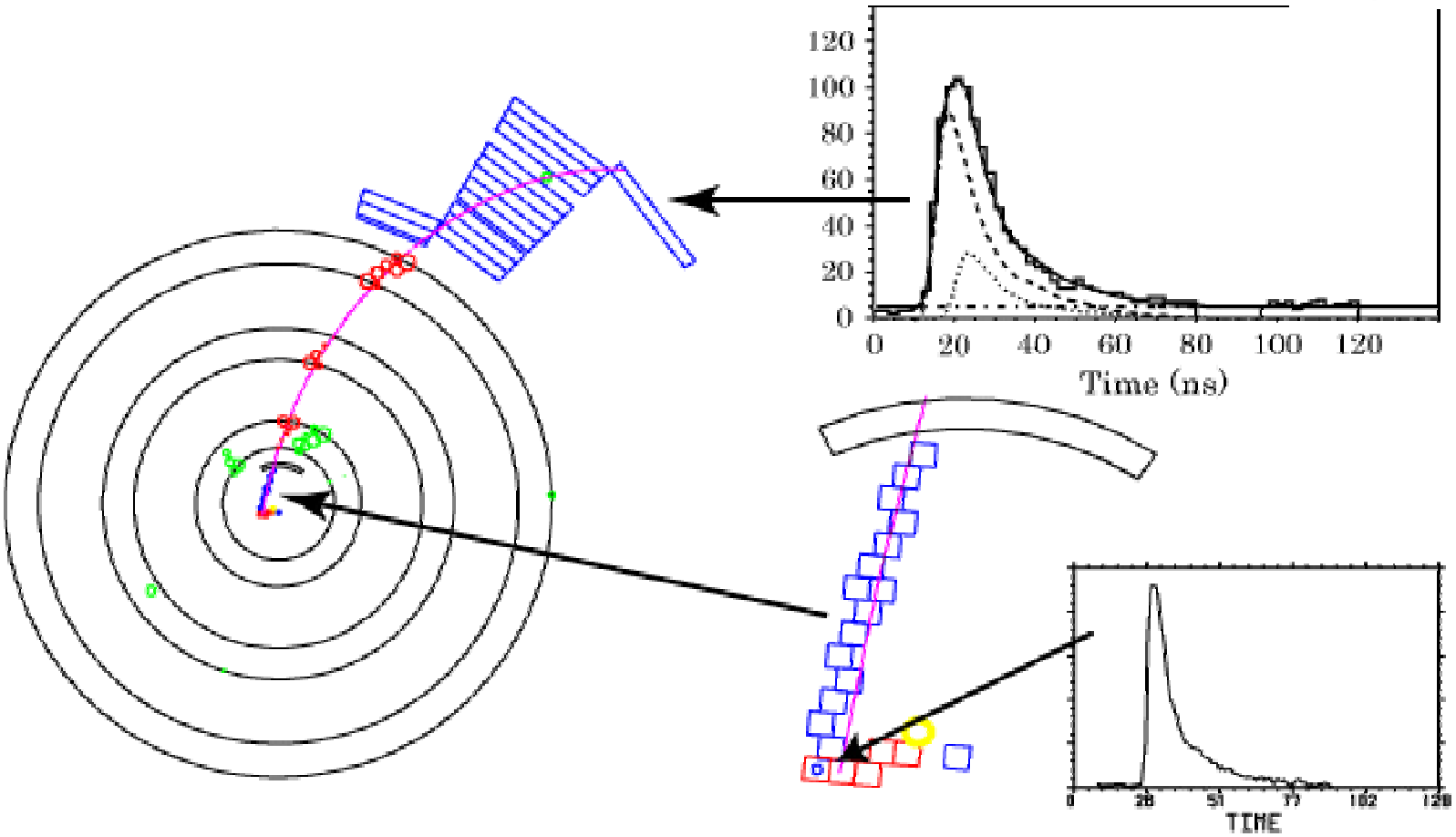
Open the Box

- 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:

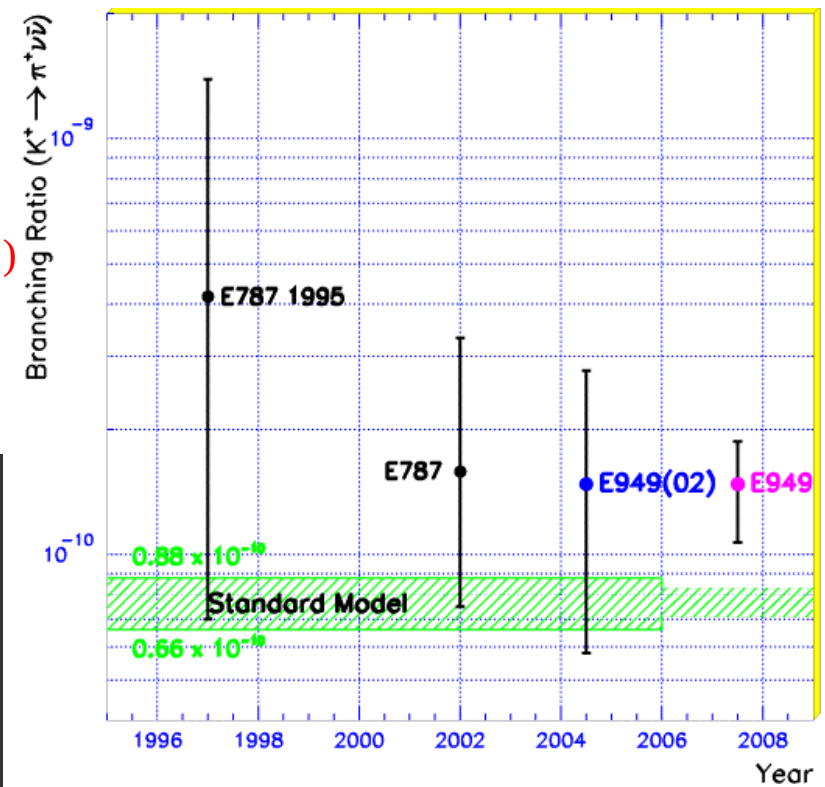
$$Br(K^+ \to p\,^+ n n^-) = 0.96^{+4.09}_{-0.47} \times 10^{-10} \text{ (68\% CL)}$$

- Combine E787 and E949 results

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

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.

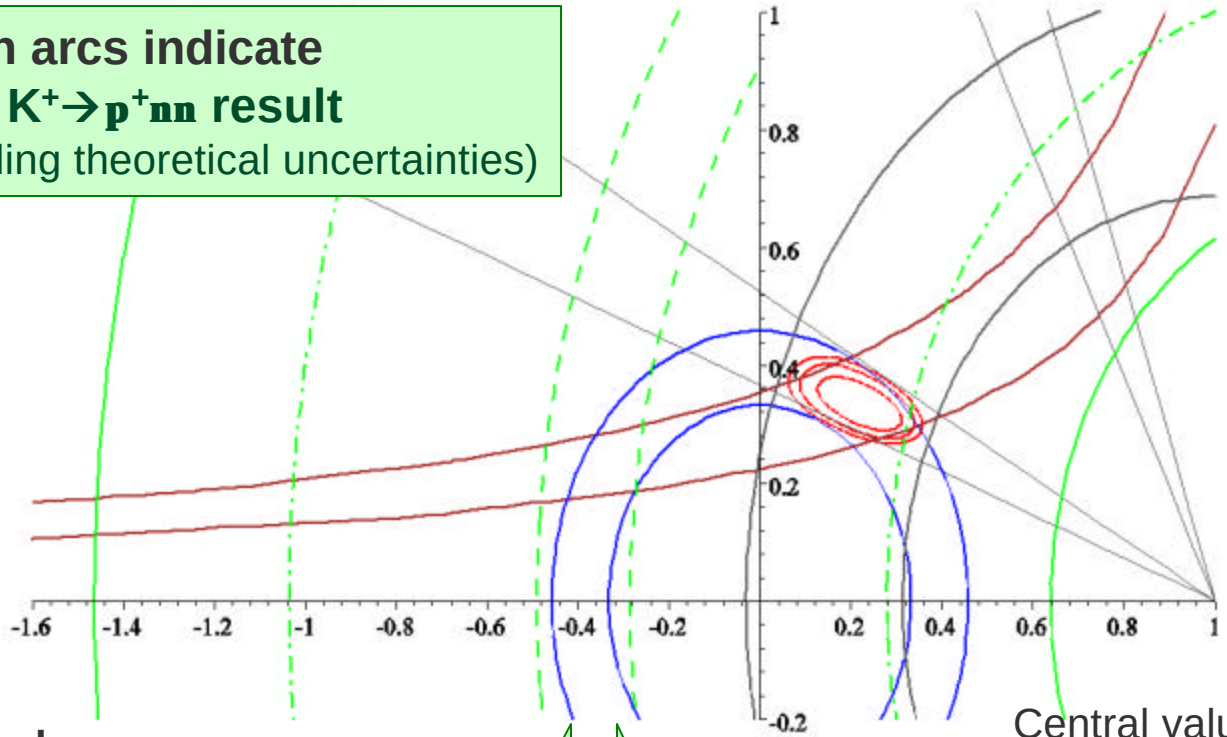
(~60 weeks)

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

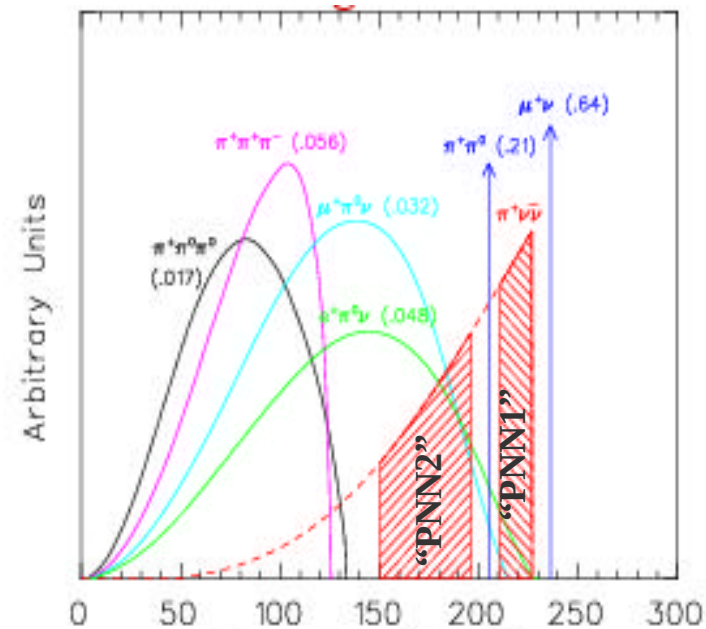
68% interval

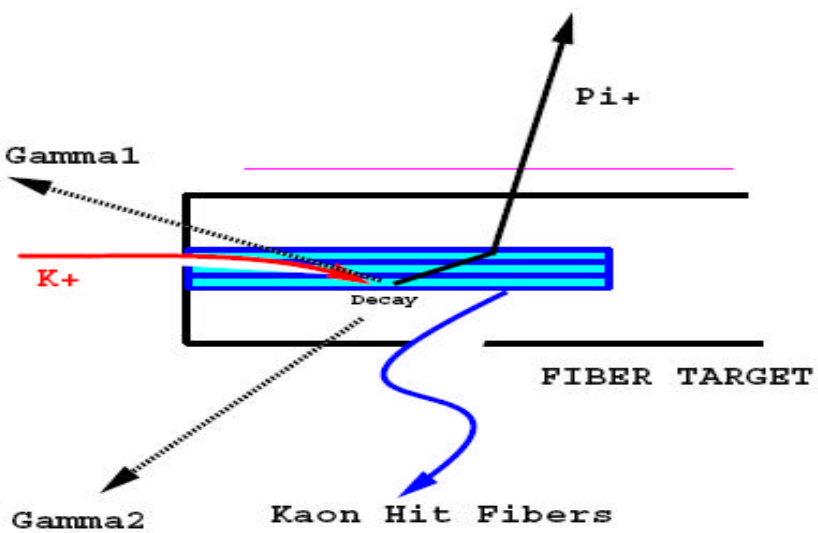
90% interval

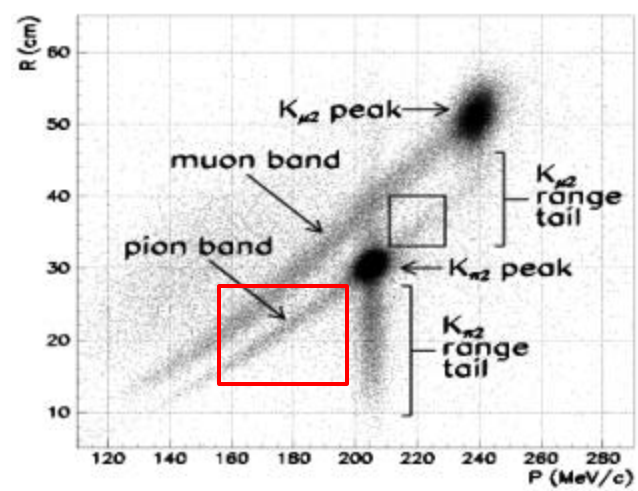
Central value
off the "SM"
→ **Need more data!!**

PNN2 analysis

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





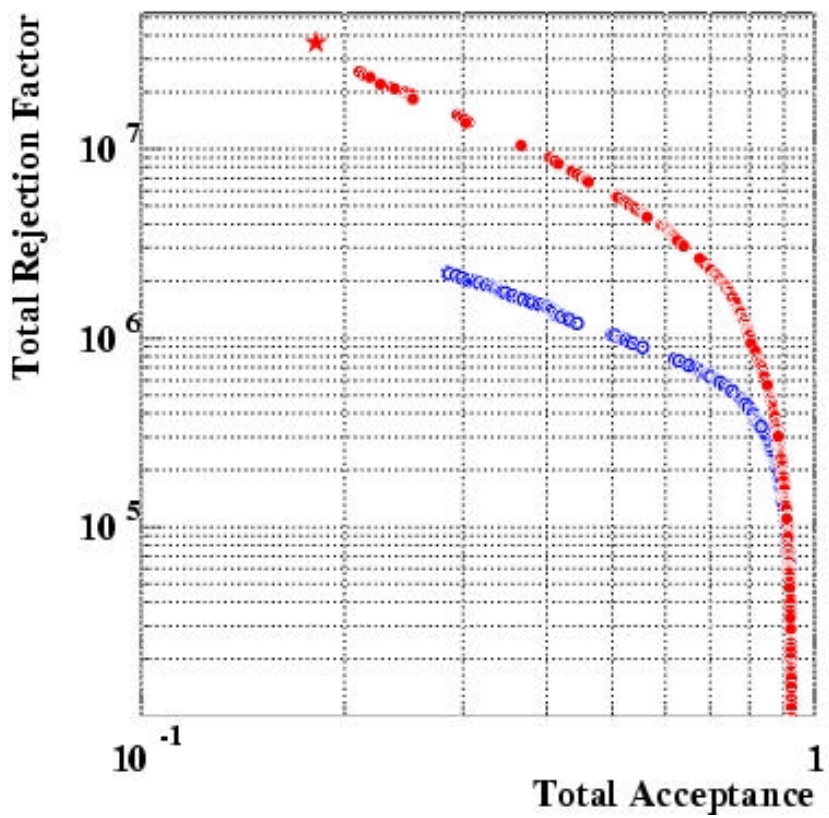


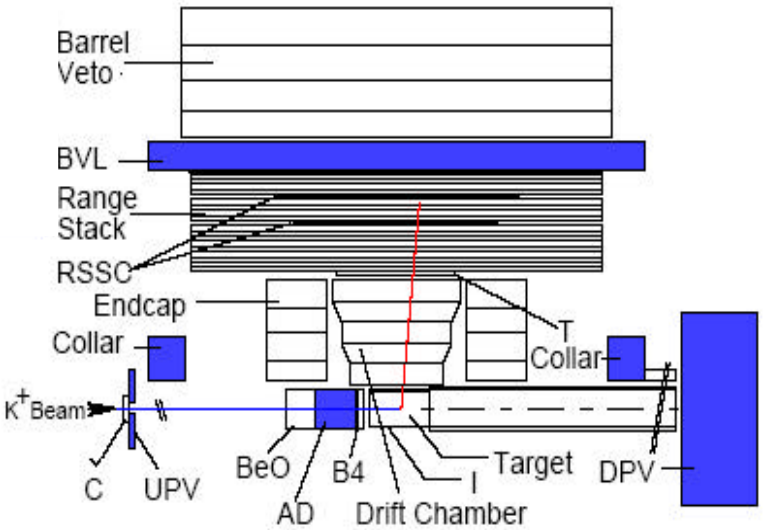
PNN2 analysis (2)

- *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)

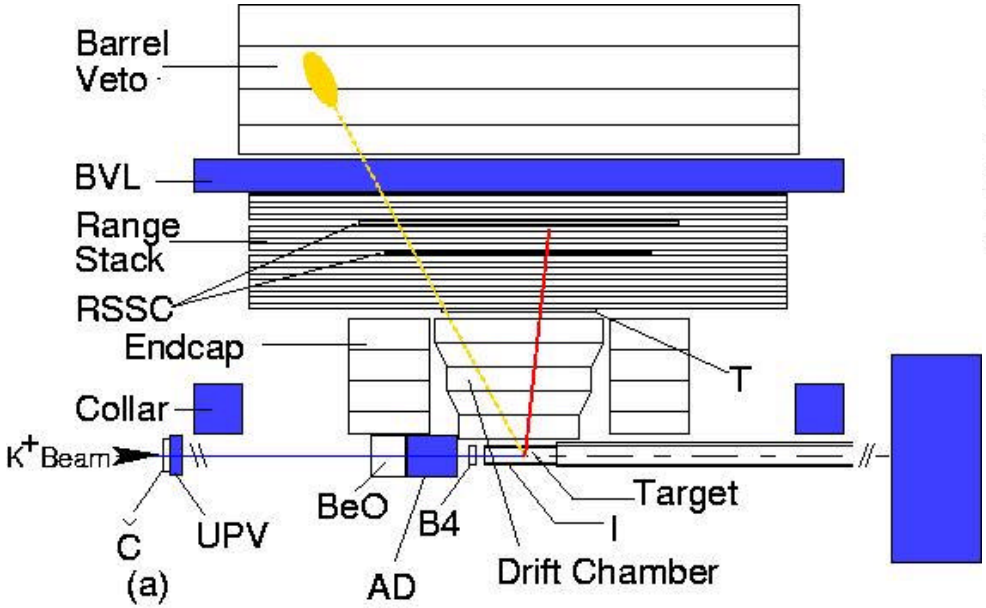
- $140<p_p<195$ MeV/c
- 1 candidate event
- Expected background of 1.22 +/- 0.24 events
- $BR(K^+\rightarrow\pi^+ \nu \nu) < 22 \times 10^{-10}$
- Background limited, with S/N<0.2

E949 Data:

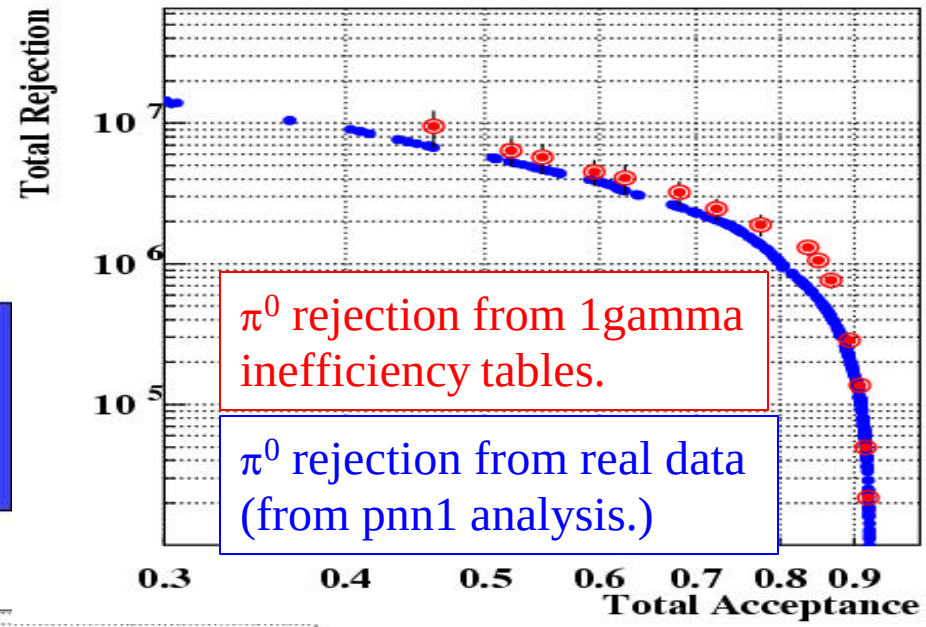
- E949 data is being worked on now – improved photon veto rejection will improve the limit and may allow observation of $K^+\rightarrow\pi^+\nu\nu$ signal.

Other Physics

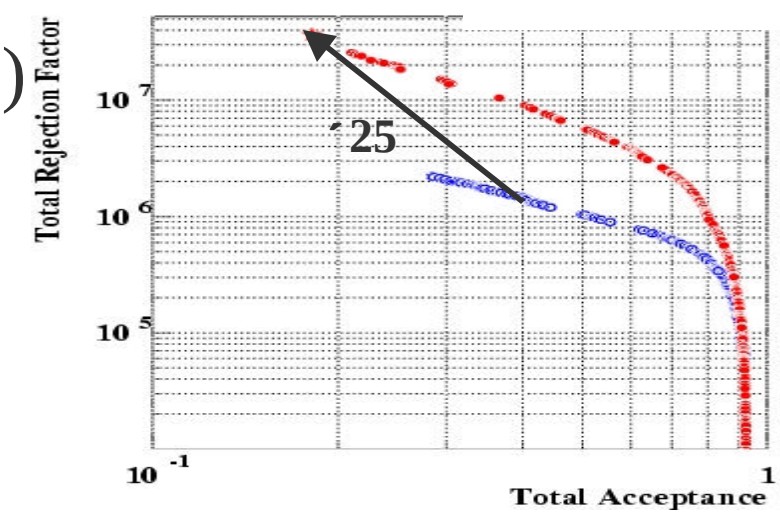
$K^+ \to \pi^+ \gamma\gamma$ (and $K^+ \to \pi^+ \gamma$)



$\pi^0 \to \nu\nu$



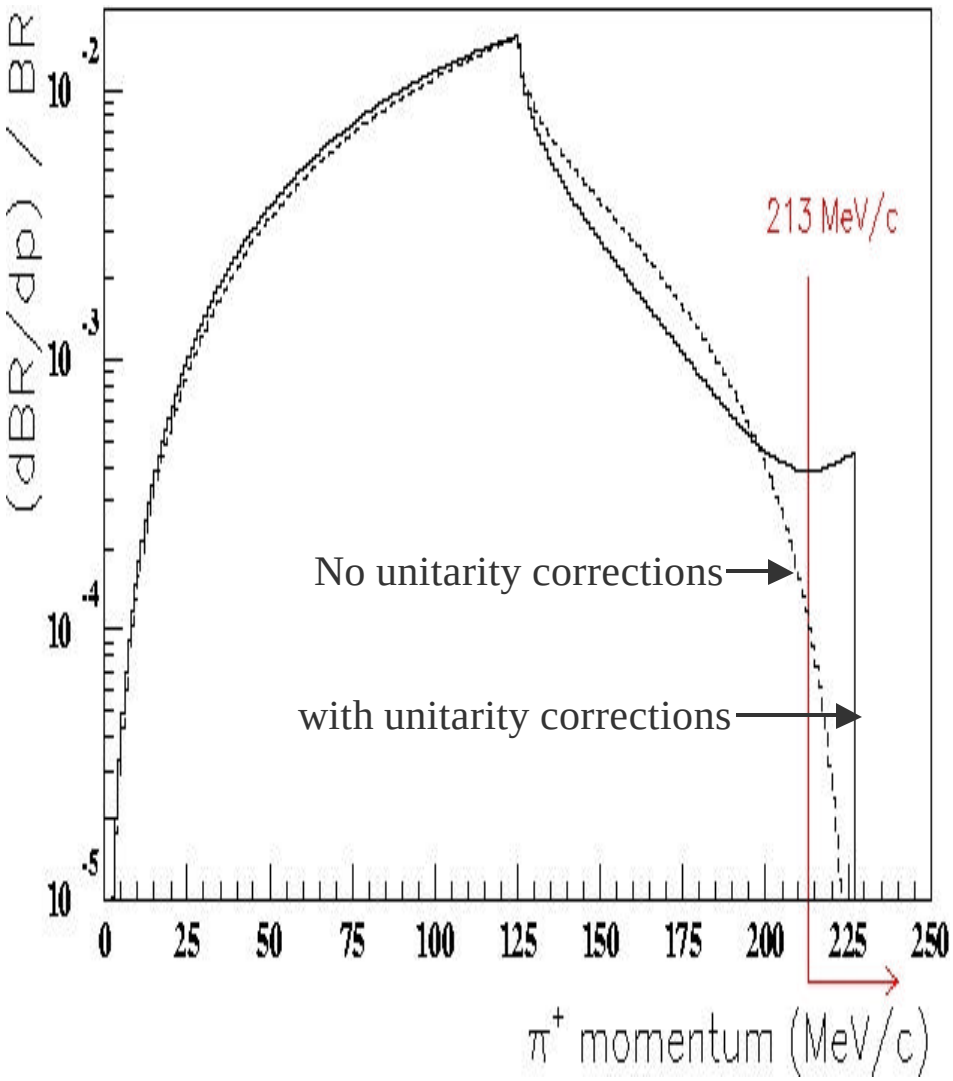
$K^+ \to \pi^+ \nu\nu$ (pnn2)



..and from E787:

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

$K^+ \rightarrow \pi^+ \gamma\gamma$



- Striking difference near the endpoint between $K^+ \rightarrow \pi^+ \gamma\gamma$ w/UC vs. w/oUC
- Endpoint is interesting in $K^0 \rightarrow \pi^0 \gamma\gamma$ for the CP-conserving contribution to $K^0 \rightarrow \pi^0 l^+ l^-$
- E787 observed 26 events with $100 < P_{\pi+} < 180$ MeV/c; good fit to c=1.8±0.6 w/UC and c=1.6±0.6 w/oUC.

$B(K^+ \rightarrow \pi^+ \gamma\gamma{:}100 < P_{\pi+} < 180\text{MeV/c}) = (6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$

- First run of E949 should see events near endpoint w/UC
- Same analysis strategy and techniques as E787/E949 $K^+ \rightarrow \pi^+ \nu\nu$
- Bkg = 0.19±0.07

  Acc = $(3.72 \pm 0.14) \times 10^{-4}$ UC

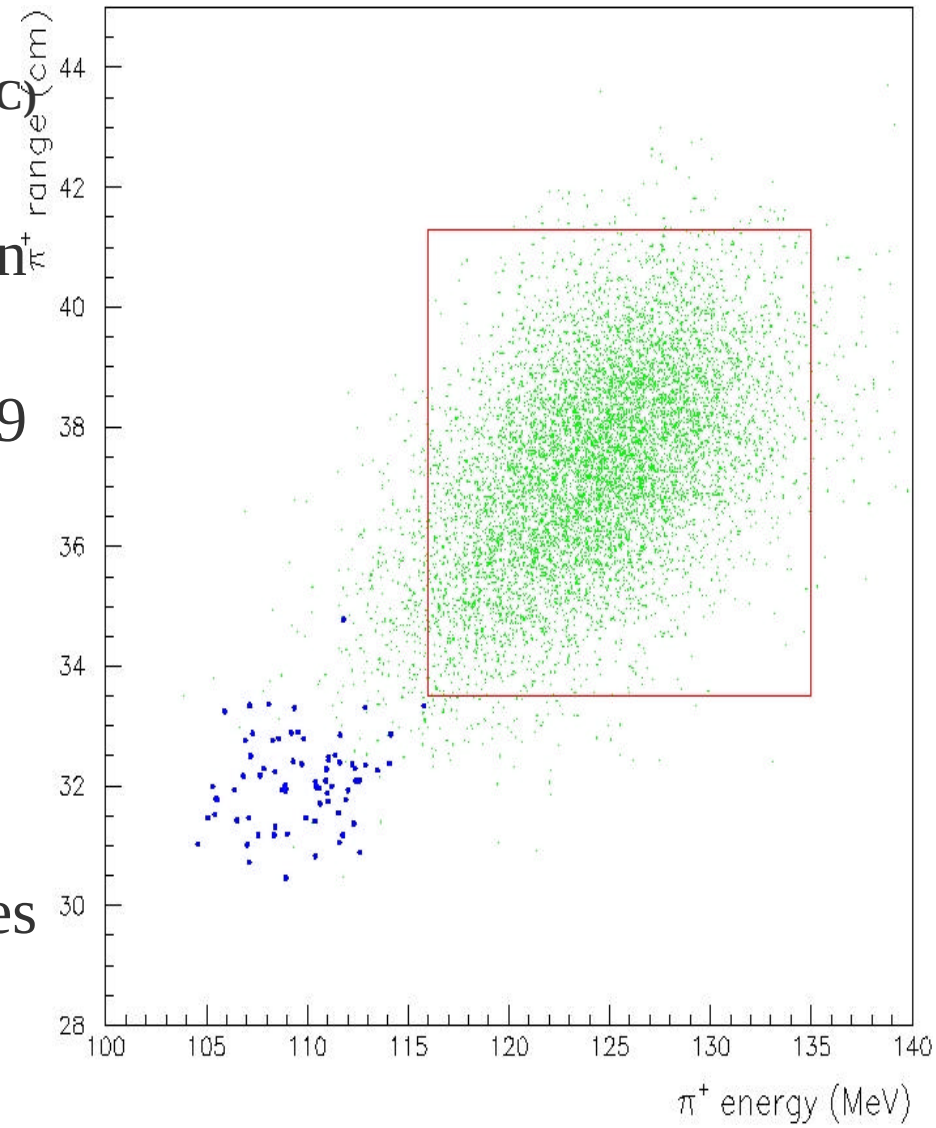
  Acc = $(1.10 \pm 0.04) \times 10^{-4}$ w/oUC

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

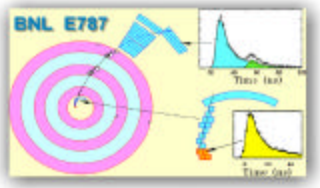
- No events are observed!
- **B(K⁺ ® p⁺gg:P_{p+}>213MeV/c)<8.3´10^{-9} (UC)**
- **B(K⁺ ® p⁺gg:P_{p+}>213MeV/c)<2.3´10^{-8}**
- Limit in this region is ×8 better than E787
- Need the rest of the scheduled E949 data.

- Same data is used to search for $K^+ \to \pi^+ \gamma$ (forbidden by angular momentum and gauge invariance), allowed in noncommutative theories
- **B(K⁺ ® p⁺g) < 2.3´10^{-9}**
- Limit is ×150 better than E787

hep-ex/0505069



All limits are (90% CL)



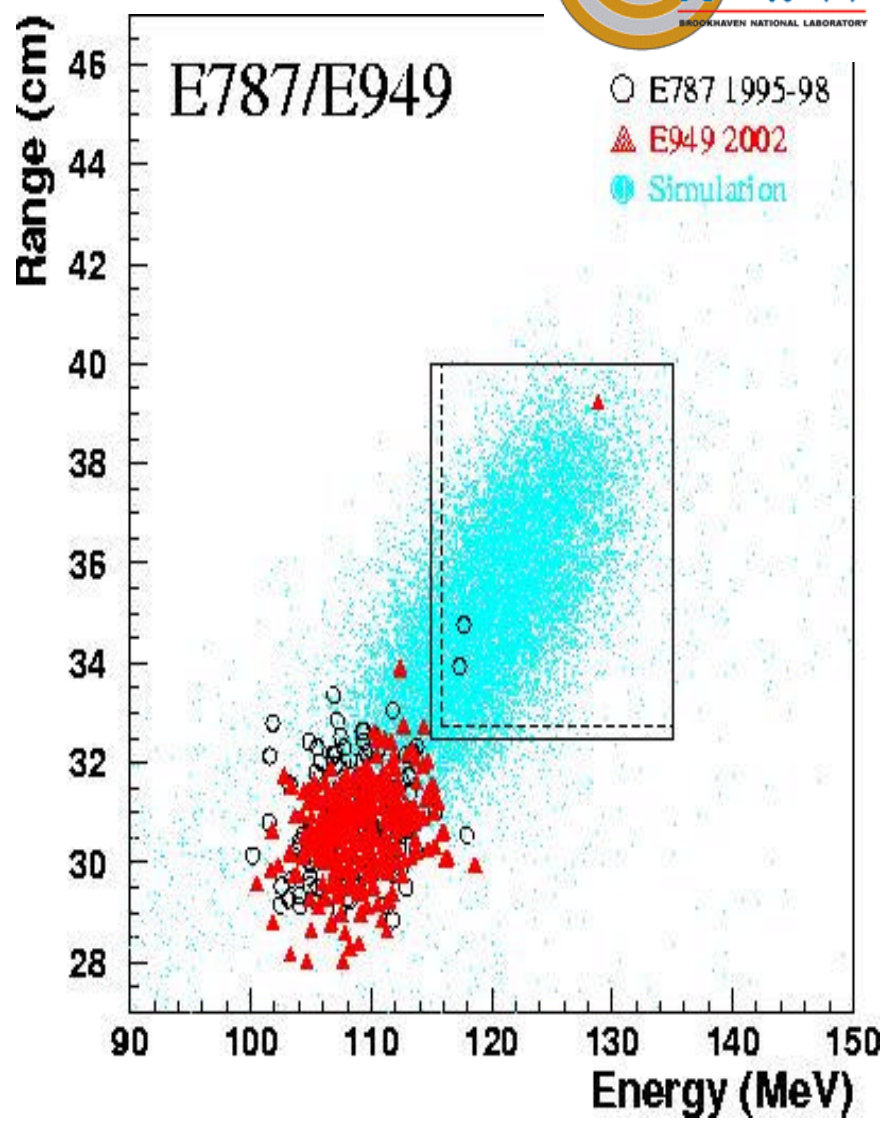
Summary & Outlook (1)

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

$$B(K^+ \to p^+ nn) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$

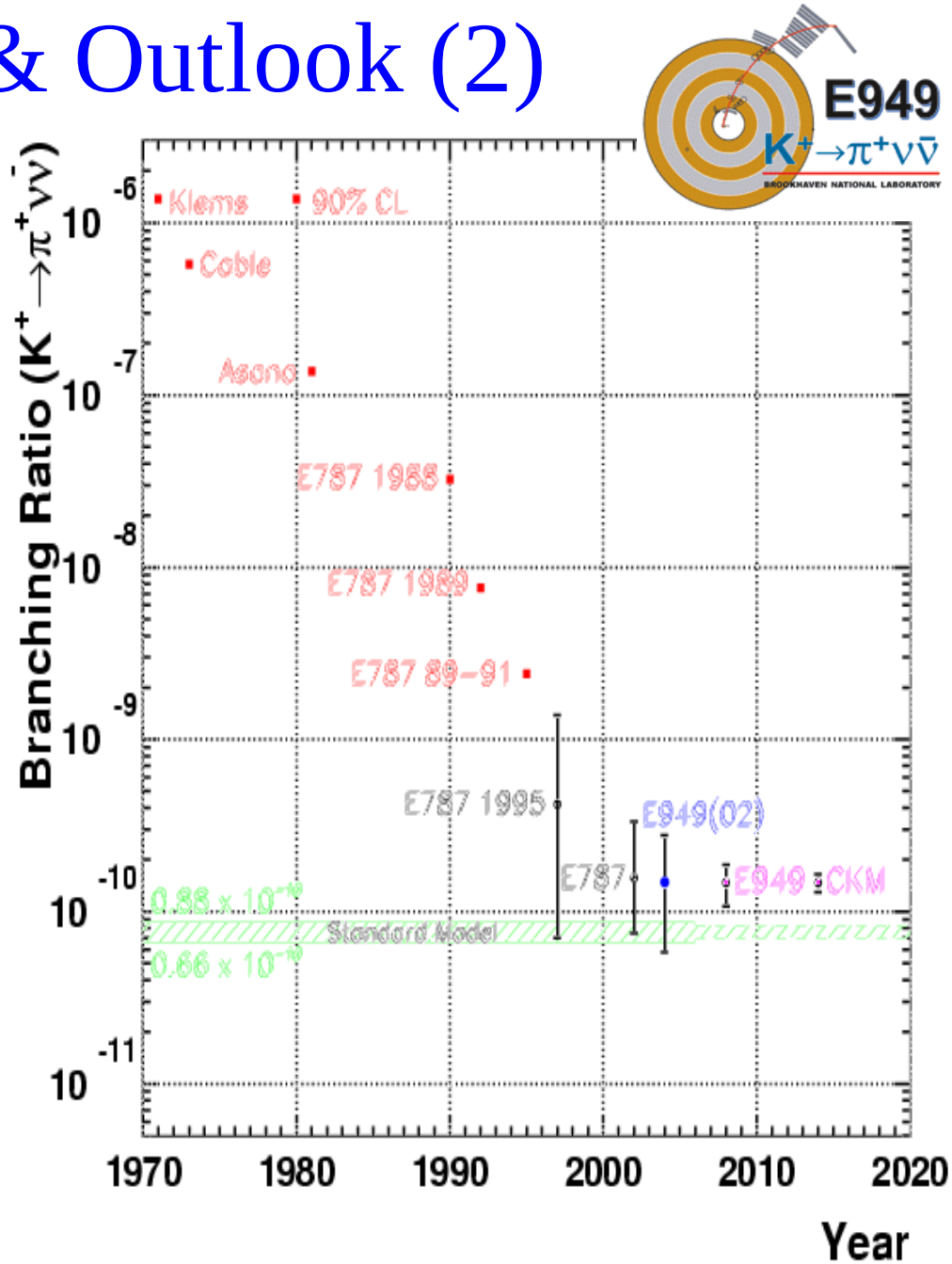
(SM: 0.8×10^{-10})

- 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 $K^+ \rightarrow \pi^+ \nu \nu$ in the 1995 data set
- The three events observed the BR measured by E787/E949 remains higher than expected
- …more data is needed!

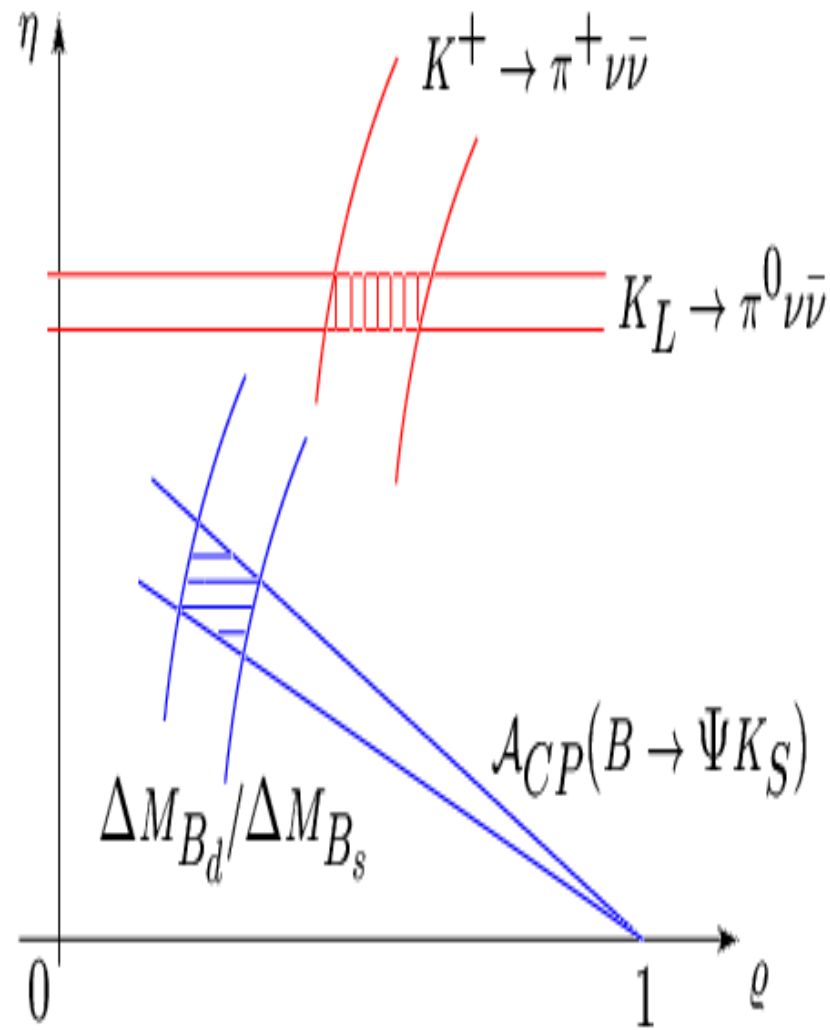


Summary & Outlook (3)

- E949 remains an approved but now un-funded DOE experiment.
- CKM was cancelled by DOE. Kplus is stopped by FNAL.
- NSF has expressed interest in $K^+ \rightarrow \pi^+ \nu\nu$: a proposal to NSF to complete E949 has been awaiting RSVP management reorganization and RSVP construction funding, and then…
- What about the future: a high rate unseparated experiment at CERN looks promising? or a stopped JPARC experiment?
- Two $K_L \rightarrow \pi^0 \nu\nu$ experiments are now on reasonably strong footing (E391a has data; KOPIO construction funding has been appropriated).
- 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!

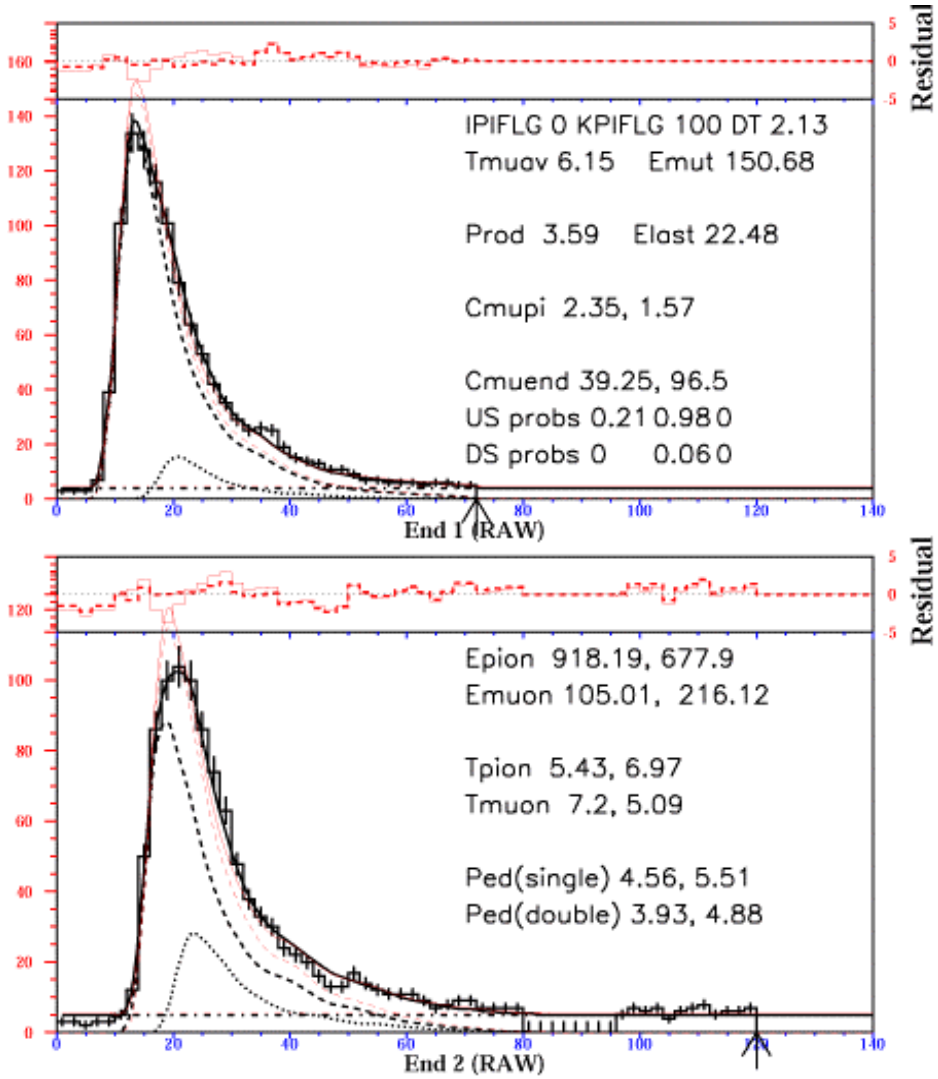
Summary & Outlook (4)

- 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 in 1-2 years 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.



Backup

Pulse fitting in the π^+ stopping counter

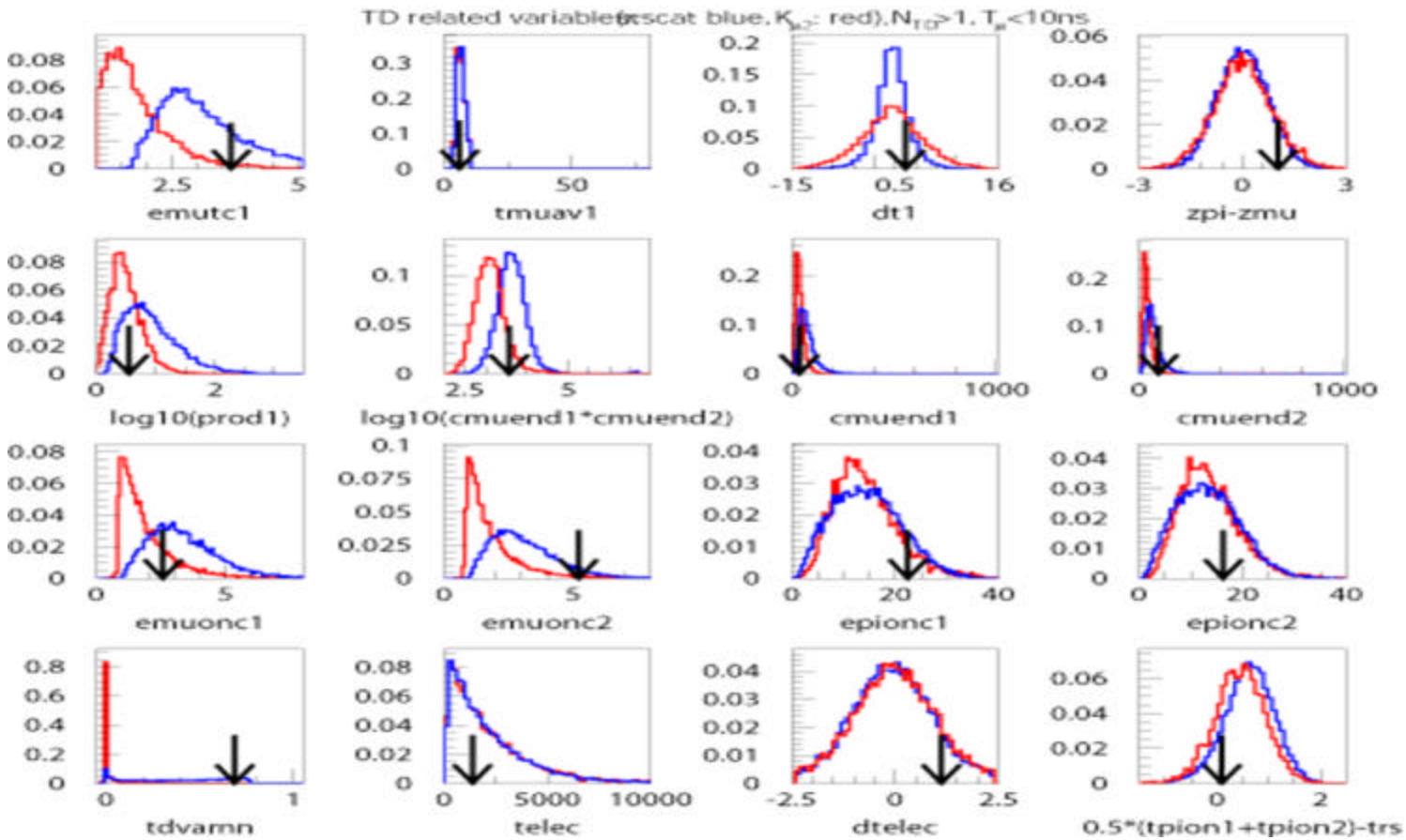


TD properties of the candidate

- Plots with π^+ and μ^+ samples

Arrows show the candidate event

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



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 $\mathbf{A_i}$

$$\mathbf{S_i} = \mathbf{BR} \text{ (as a free parameter) } \times \mathbf{N_K} \times \mathbf{A_i}$$

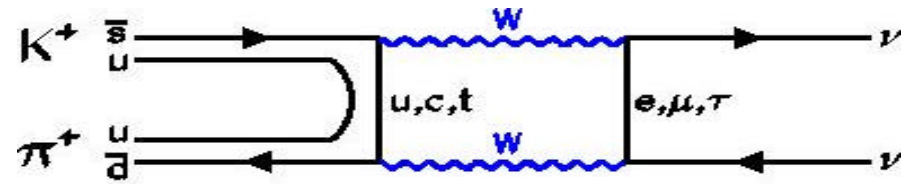
- Likelihood technique in small S_i, b_i (T.Junk, NIM **A434**, 435 (99))
  - Ratio of two Poisson probabilities (S+B or B only)
  - Estimator defined as

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

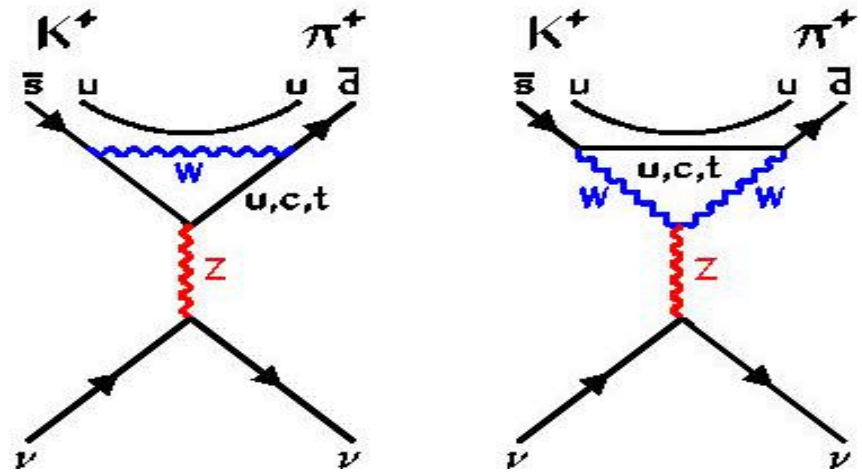
($\mathbf{d_i}$ = # of observed candidate in the cell)

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

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

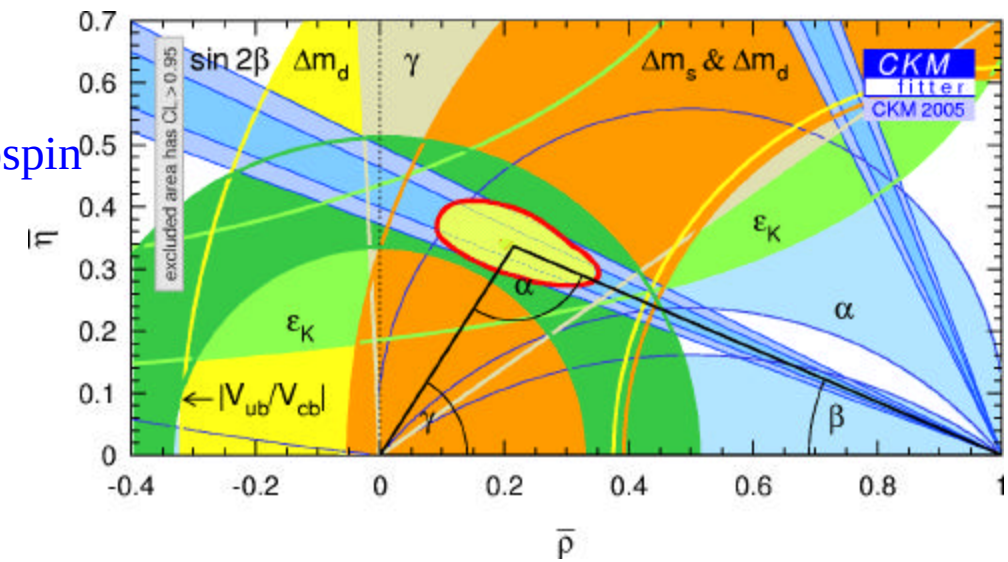


One of the Golden Modes for study of the CKM matrix and CP violation. The rate can be calculated precisely from fundamental SM parameters (~8%), and any deviation in the measured rate will be a clear signal for new physics.



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



	E787 Prop	E787 (run)	E949 (run)	E949 Prop	CKM Prop	Kplus LOI	JPARC L04	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%	6s/28s 21%	1.7s/4.4s 39%	4.8s/16.8s 29%
Teff/Tsp	1?	0.85	0.92	0.85	1?	1?	0.9?	0.63
$\|P_K\|$ (MeV/c)	710	730	710	730	22,000	45,000	550	75,000
K/(K+p+p)	0.25	0.8	0.7	0.8	0.7	0.04	0.75	0.06
K/sec (spill)	1.0 MHz	4 MHz	6 MHz	5 MHz	30 MHz	10 MHz	18 MHz	25 MHz
K/sec	0.4 MHz	1.8 MHz	2.4 MHz	3.1 MHz	10 MHz	2.1 MHz	7.0 MHz	7.5 MHz
Flux/Teff (spill)	5.5 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	38%	23%	27%	26%	13%	17%	40%	9%
K-decay/sec	0.15 MHz	0.41 MHz	0.65 MHz	0.8 MHz	1.7 MHz	0.4 MHz	2.8 MHz	0.6 MHz
LT*eff	1*0.5?	0.78*0.40	0.74*0.52	0.82*0.71?	1*0.71?	1*0.71?	0.8*0.66?	1*0.67?
weeks/year	17	20	12	25	39	39	25	12.9
years	1	4	1	2.4	2	3	3	2
Total K 'decay'	7.5×10^{11}	6.2×10^{12}	1.8×10^{12}	1.7×10^{13}	5.8×10^{13}	1.8×10^{13}	7×10^{13}	7×10^{12}
pnn1 Acc.	1.5%	0.2%	0.22%	0.3%	1.6%	2.0%	0.6%	5%
pnn1 (/yr)	1(1)	1.2(0.3)	0.4(0.4)	7(3)	95(47)	36(12)	40(13)	17(8)
pnn2 (/yr)		0.15(0.07)	0.4(0.4)?	5(3)	130(65)	54(18)	40(13)?	17(8)
Events (/20wk)	1(1.3)	1.3(0.4)	0.8(1.3)?	12(4)	225(58)	90(15)	80(21)	34(26)