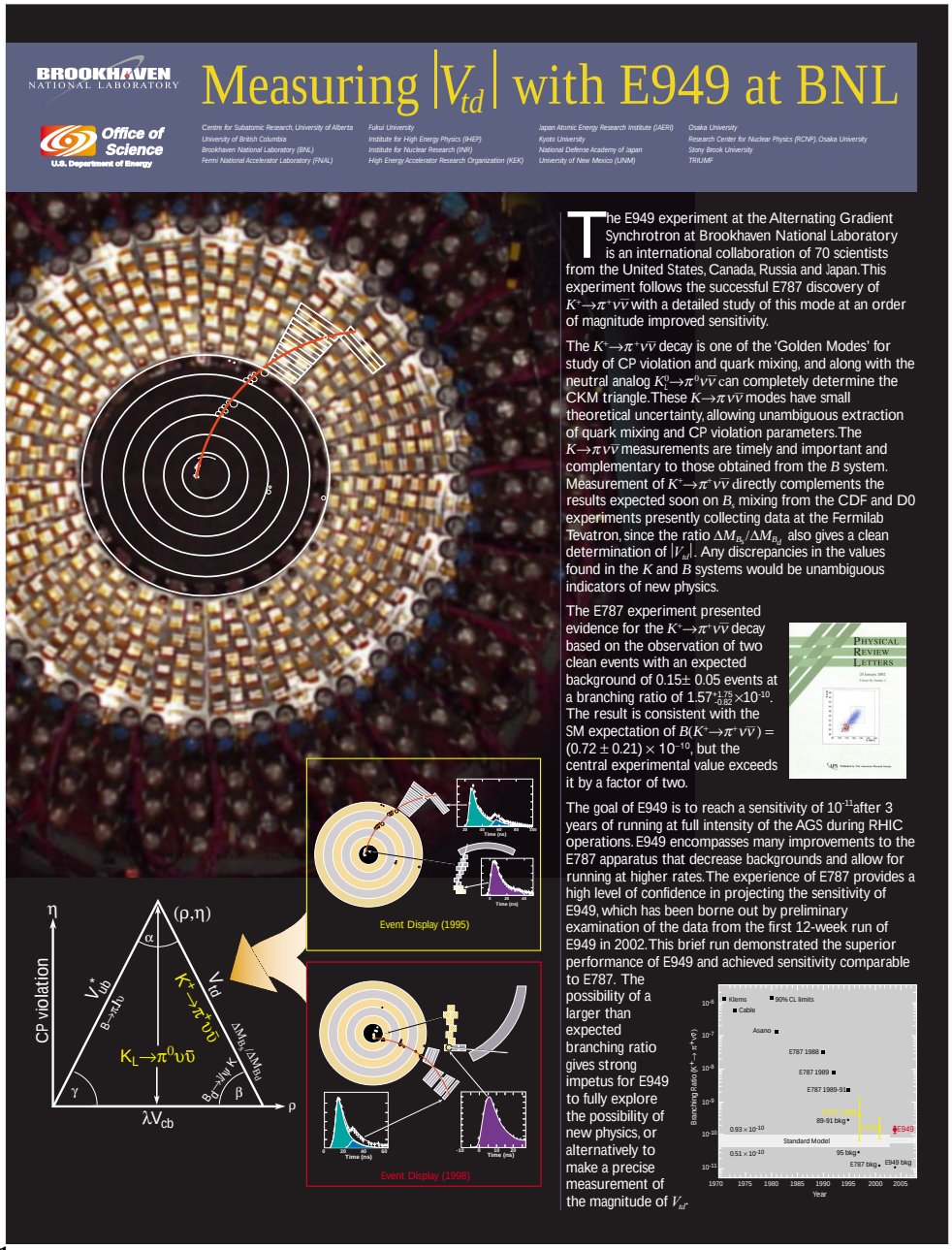
First Results from BNL E949 on $K^+ \to \pi^+ \nu\bar{\nu}$

Steve Kettell

BNL

- Introduction & Motivation
- Overview of the experiment
- ...some details
- The results
- Conclusions

Fermilab Wine & Cheese, April 1, 2004



E949

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

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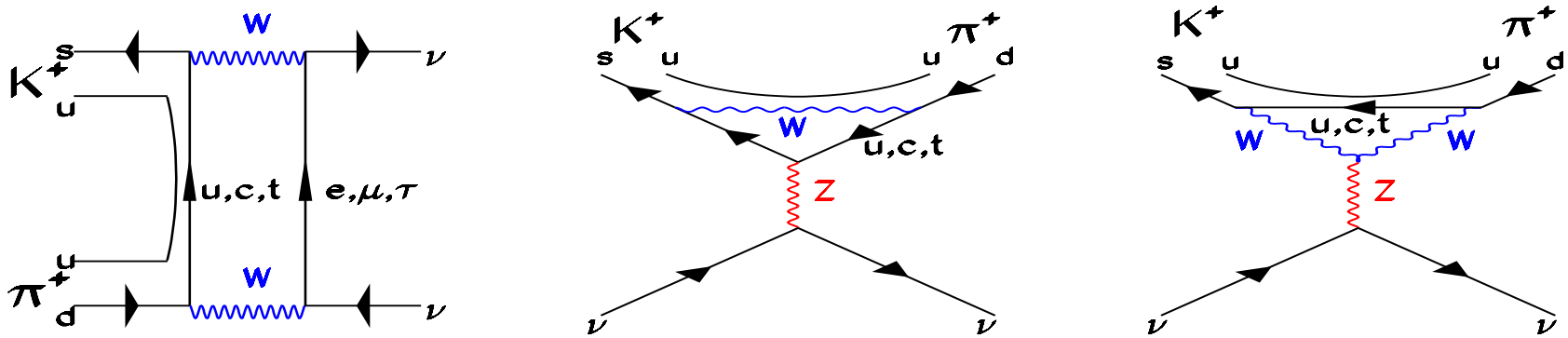
TRIUMF

Students and post-docs in red.

∼70 physicists, plus a lot of hard work from earlier E787 collaborators.

$K^+ \to \pi^+ \nu\overline{\nu}$ in the SM

$K^+ \to \pi^+ \nu\bar{\nu}$, a FCNC, is forbidden at 1st order and suppressed at 2nd order; since $m_t >> m_c, m_u$ $K^+ \to \pi^+ \nu\bar{\nu}$ proceeds at a small rate and with strong sensitivity to $|V_{td}|$.



The intrinsic uncertainty in calculating $\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}\ )$ from the fundamental CKM parameters is small (and may get smaller):

- hadronic matrix element is extracted from $K^+ \to \pi^0 e^+ \nu$ (isospin and p.s. corrections)
- NLO QCD calculation has significantly reduced the uncertainty, dominated by c-quark
- long distance effects are negligible
- 2-loop electroweak calculations completed (correction $\mathcal{O}(1\%)$)
- total intrinsic theoretical uncertainty is $\sim$5%

$$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = \frac{\kappa_+ \alpha^2 B(K^+ \to \pi^\circ e^+ \nu_e\ )}{2\pi^2 \sin^4\theta_W |V_{us}|^{\ 2}} \sum_l |X_t \lambda_t + X_c \lambda_c|^2$$

$$= (0.77 \pm 0.11) \times 10^{-10}$$

where $|\lambda_i| \equiv |V_{is}^* V_{id}|, i = u, c, t$. The $\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}\ )$ uncertainty is currently limited by our imperfect knowledge of $|V_{td}|$. $K^+ \to \pi^+ \nu\overline{\nu}$ provides a clean determination of $|V_{td}|$.

Unitarity Triangle

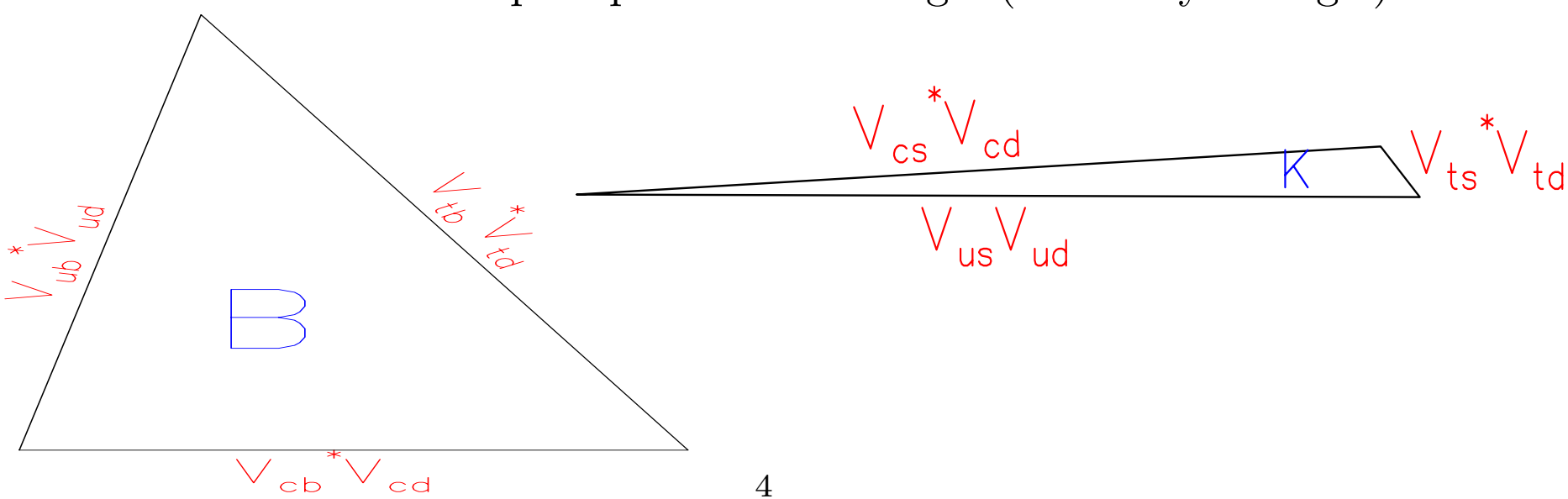
In the SM the CKM matrix relates flavor and weak eigenstates. and with 3 generations naturally explains CP violation through the phase $\bar{\eta}$:

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

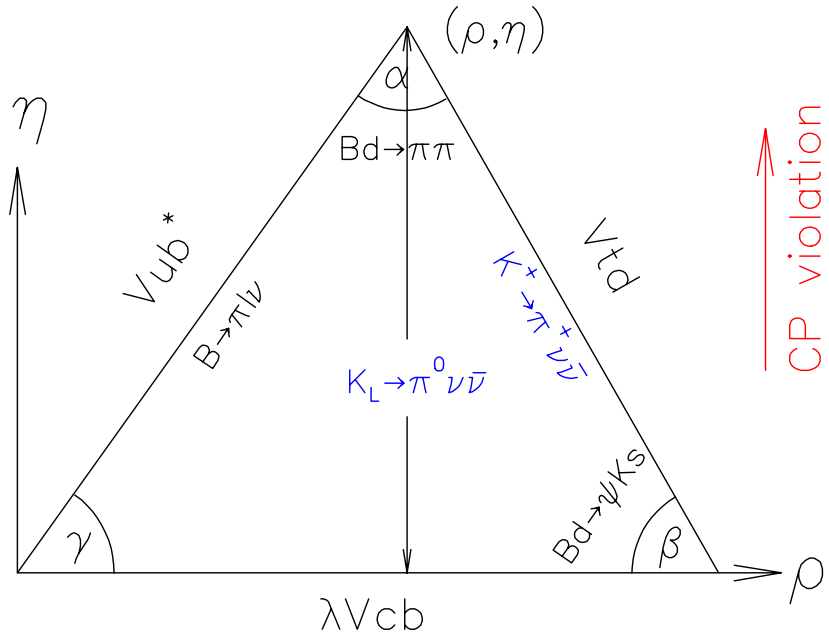
This gives 6 relations equal to 0. For example:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{or} \quad \lambda_u + \lambda_c + \lambda_t = 0$$

can be drawn in the complex plane as a triangle (Unitarity triangle):



Processes with small theoretical uncertainties



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

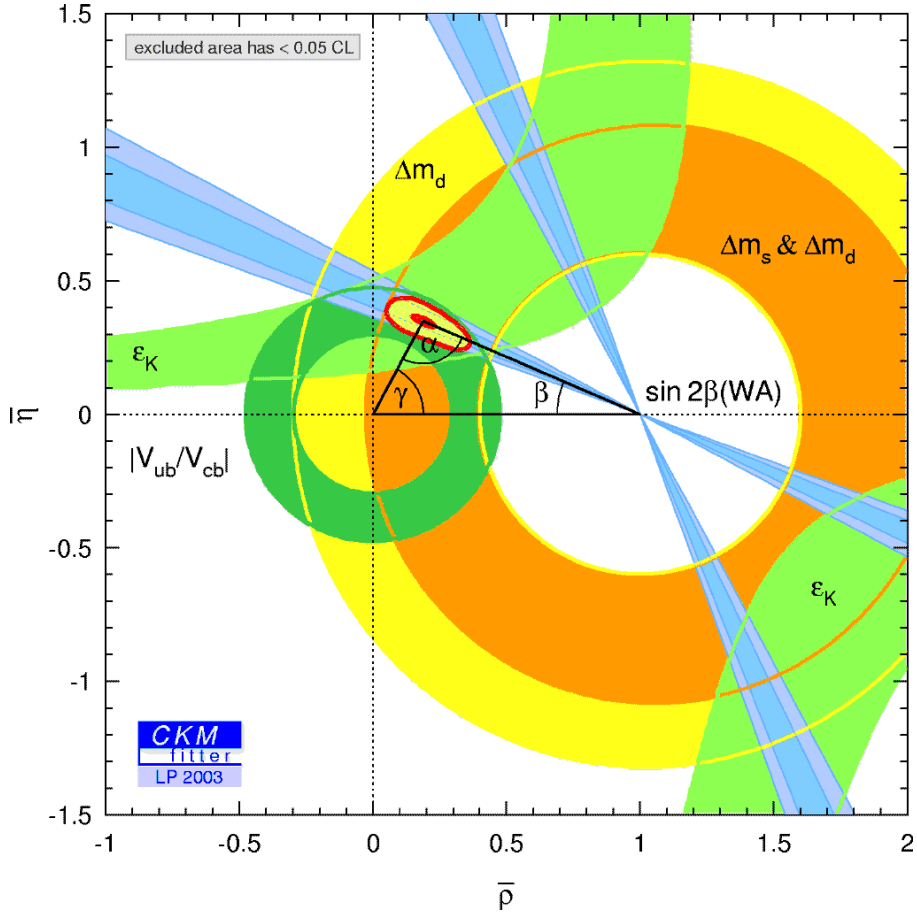
CP violating decay rate asymmetry

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

ratio of mixing frequencies of B_s and B_d mesons

- Comparison of $|V_{td}|$ from $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ and from $\Delta M_{B_s}/\Delta M_{B_d}$ provides an important test of the SM.
- Comparison of $\sin 2\beta$ from $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0 \nu\bar{\nu})/\ \mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ and from $\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S})$ is perhaps **the** definitive test of the SM picture of CP violation.

Current CKM picture



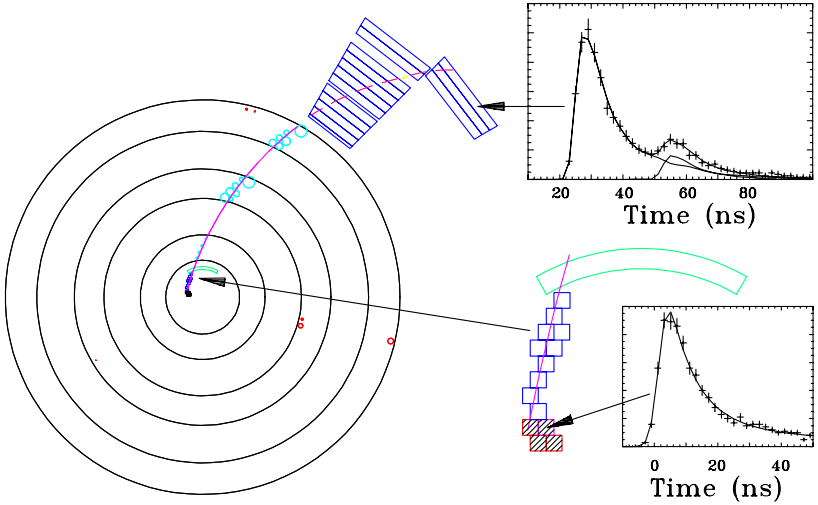
The measurement of sin2β is getting better; a better measurement of $|V_{td}|$ is called for.

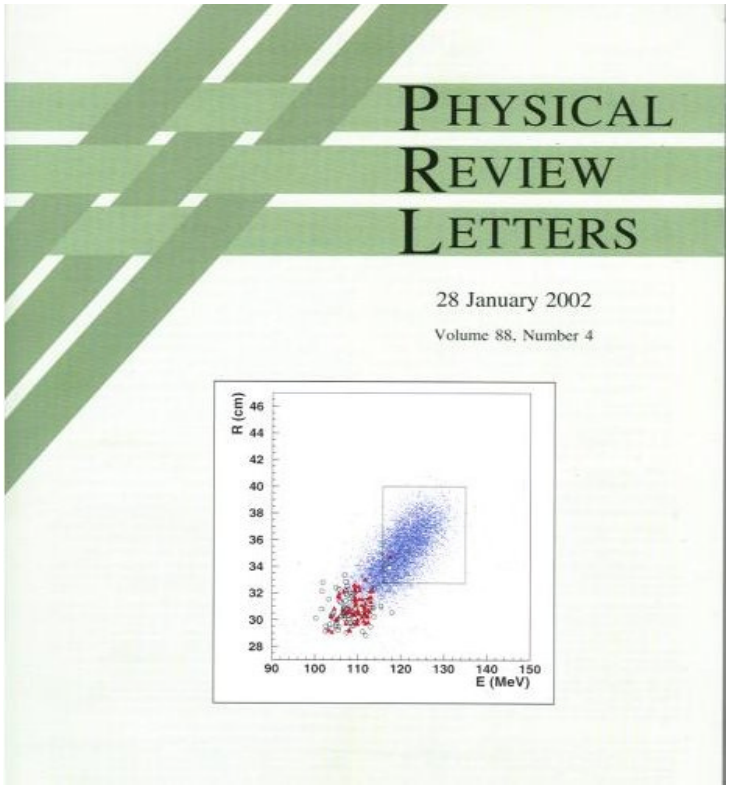
We have two modes with small theoretical ambiguity: $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+ \nu\overline{\nu}$.

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 0.4 \times 10^{-10} \times \left(P_{charm} + \frac{A^2 X(x_t)\xi}{\lambda}\sqrt{\frac{\Delta M_{B_d}}{\Delta M_{B_s}}}\right)^2 < 1.4 \times 10^{-10}$$

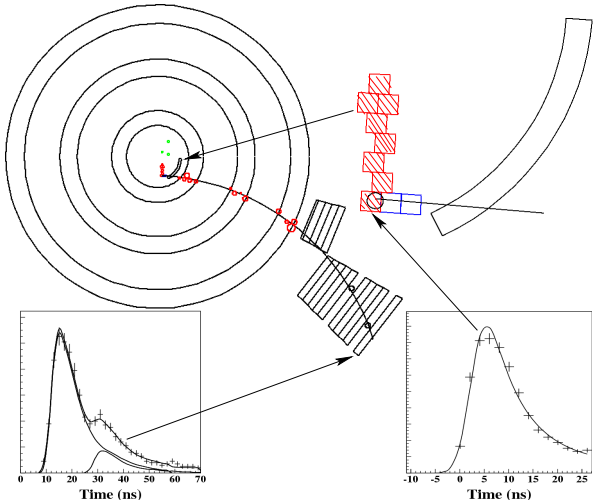
- Current limit on $\Delta M_{B_s} > 14.4 ps^{-1}$ (95% CL) (HFAG 2004)
- Current best estimate of $\xi = 1.15 \pm 0.05^{+0.12}_{-0.00}$ (CKM-LWG)
- $\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$(E787, PRL **88**, 041803 (2002))
  - $\mathcal{B}(K_L^\circ \to \pi^\circ \nu\overline{\nu}\ ) < 5.9 \times 10^{-7}$ (direct, KTeV PR**D61**, 072006 (2000))
  - $\mathcal{B}(K_L^\circ \to \pi^\circ \nu\overline{\nu}\ ) < 1.7 \times 10^{-9}$ (indirect, E787 PRL **88**, 041803 (2002))

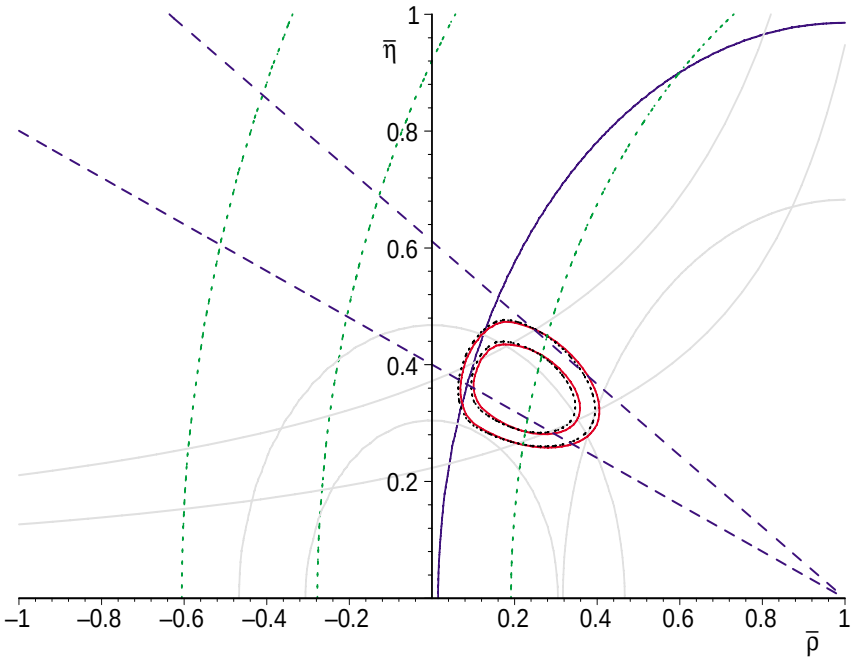
Candidate E787A





Candidate E787C





$K^+ \to \pi^+ \nu\bar{\nu}$: Difficult, but not impossible!

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}
Sensitivity (S.E.S.)	6.9×10^{-10}	0.83×10^{-10}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

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

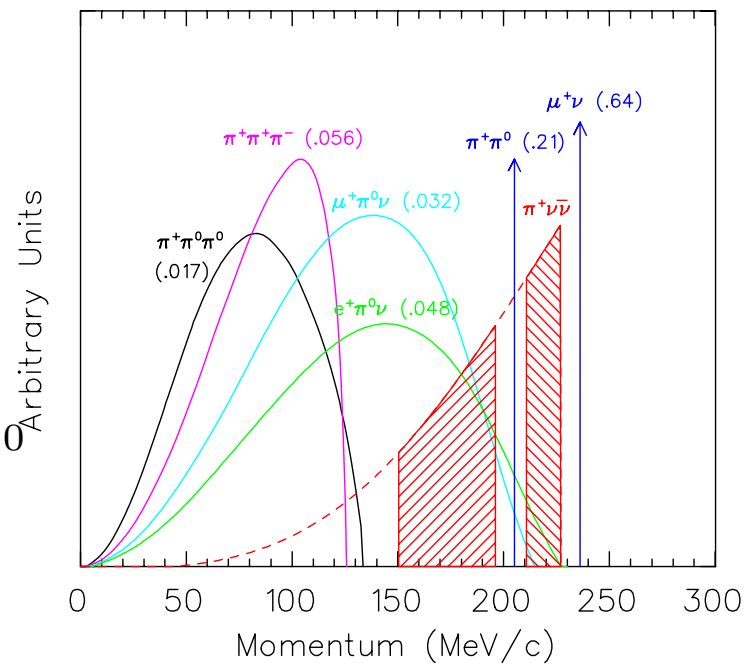
PNN1: PRL **88**, 041803 (2002).

PNN2: limit is combined from 1996 [PL **B537**, 211 (2002)] and 1997 [hep-ex/0403034] data. (1997 analysis has 27% more acceptance)

SM: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

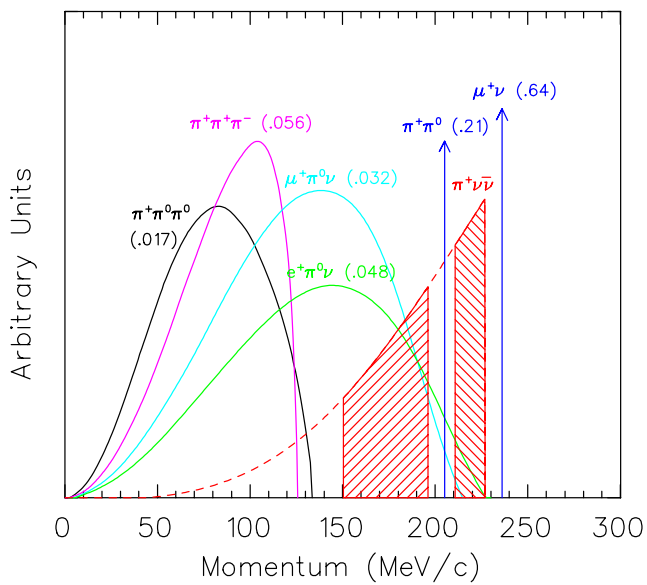
Buchalla& Buras, NP**B548** 309 (1999);

Isidori, hep-ph/0307014;Buras, hep-ph/0402112



Experimental Considerations for $K^+ \to \pi^+ \nu\overline{\nu}$

- 3-body decay with 2 missing particles $\Rightarrow 0 \leq P_{\pi^+} \leq 227\text{MeV}/c$ ...and $\mathcal{B} < 10^{-10}$
- Must veto each extra particle to $\leq 10^{-3}$
- Particle identification (PID) is essential.
- Redundant precise kinematic measurements.
- Supress backgrounds by 10^{11}



P_{π^+} **in** K^+ **rest frame**

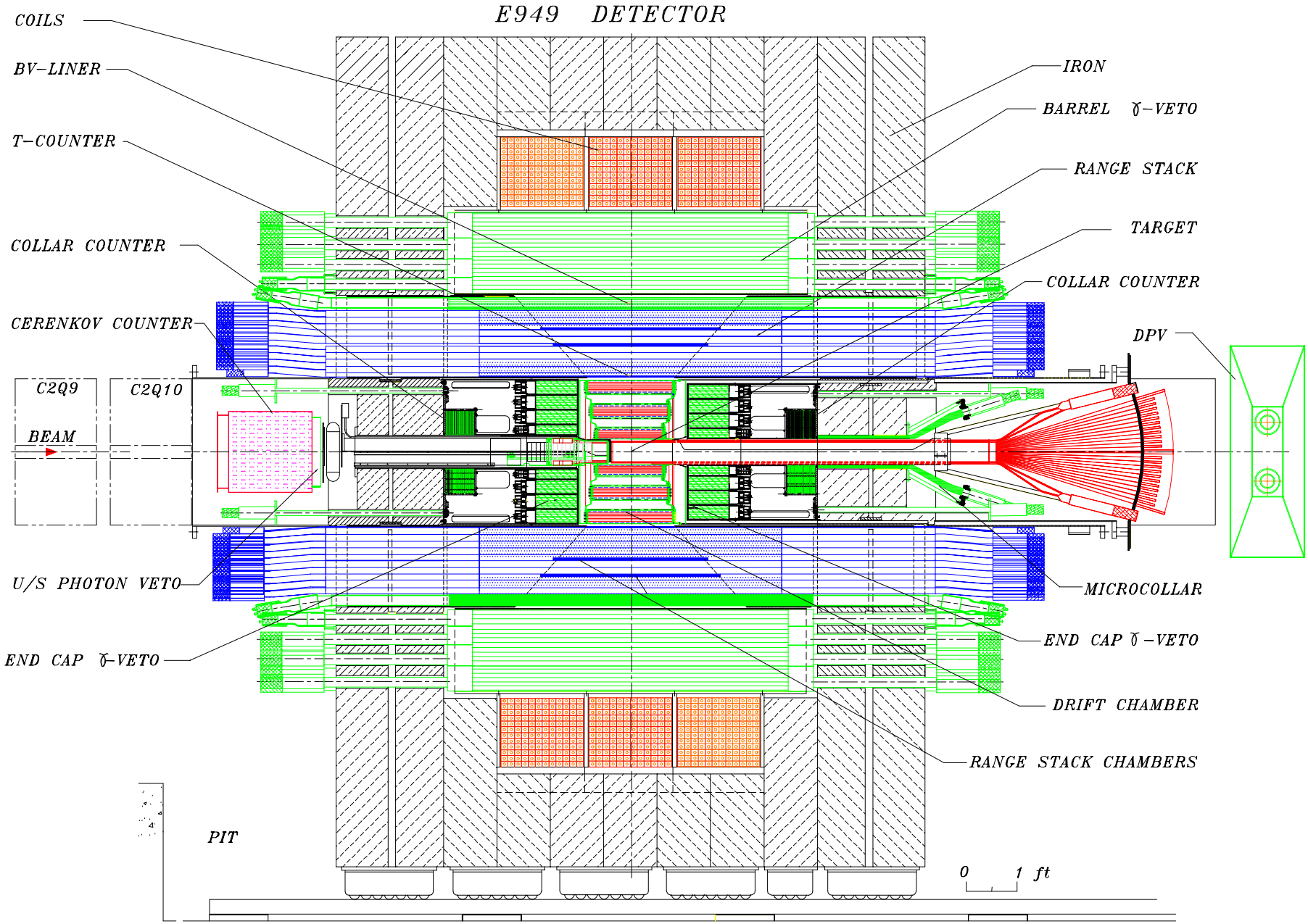
Process	$\mathcal{B}$	PID	veto	kin.	time
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	0.21	-	✓ ✓	✓	-
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	0.63	✓	-	✓	-
$K^+ \to \mu^+\nu\gamma$	0.005	✓	✓	-	-
$K^+ \to \pi^0\mu^+\nu$	0.032	✓	✓ ✓	-	-
$K^+ \to \pi^0 e^+\nu$	0.048	✓	✓ ✓	-	-
$K^+ \to \pi^+\pi^-\pi^+$	0.056	-	✓	✓ ✓	-
π^+ scatter	-	✓	-	-	✓
$K^+ n \to K_L$ p; $K_L \to \pi^+\ell^-\nu$	-	-	✓	-	✓

"kin." = kinematic suppression

"PID" = includes π/μ and K/π discrimination

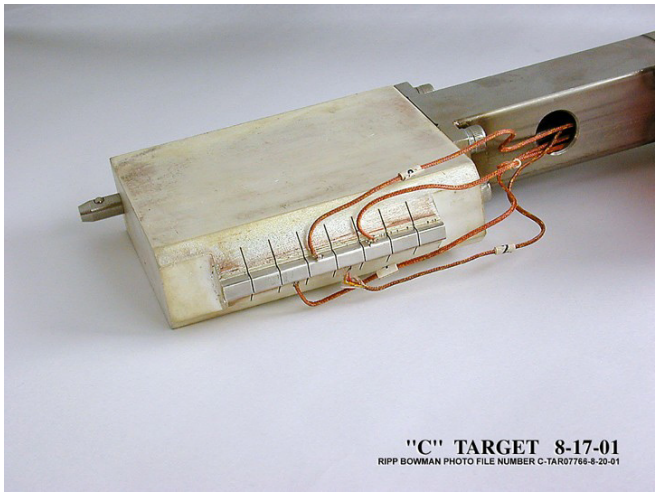
$\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = 0.77 \times 10^{-10}$

E949

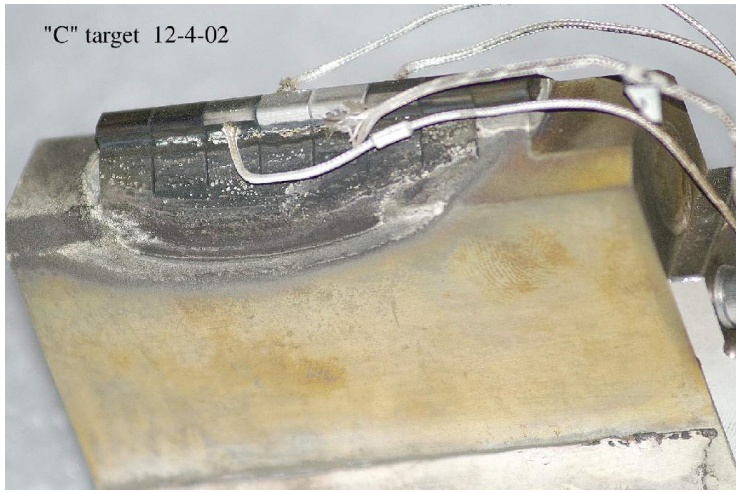

E949 DETECTOR
COILS
BV-LINER
T-COUNTER
COLLAR COUNTER
CERENKOV COUNTER
C2Q9
C2Q10
BEAM
U/S PHOTON VETO
END CAP γ-VETO
PIT
IRON
BARREL γ-VETO
RANGE STACK
TARGET
COLLAR COUNTER
DPV
MICROCOLLAR
END CAP γ-VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0 1 ft

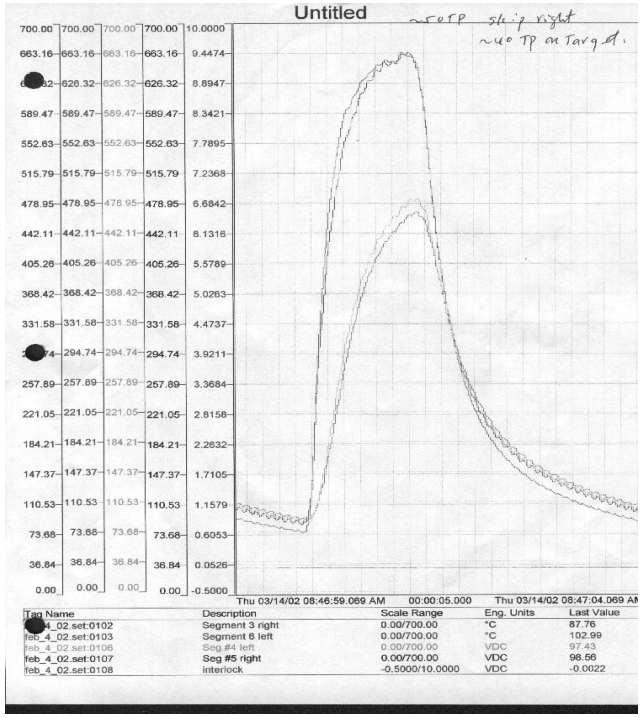
E949 production target and beamline

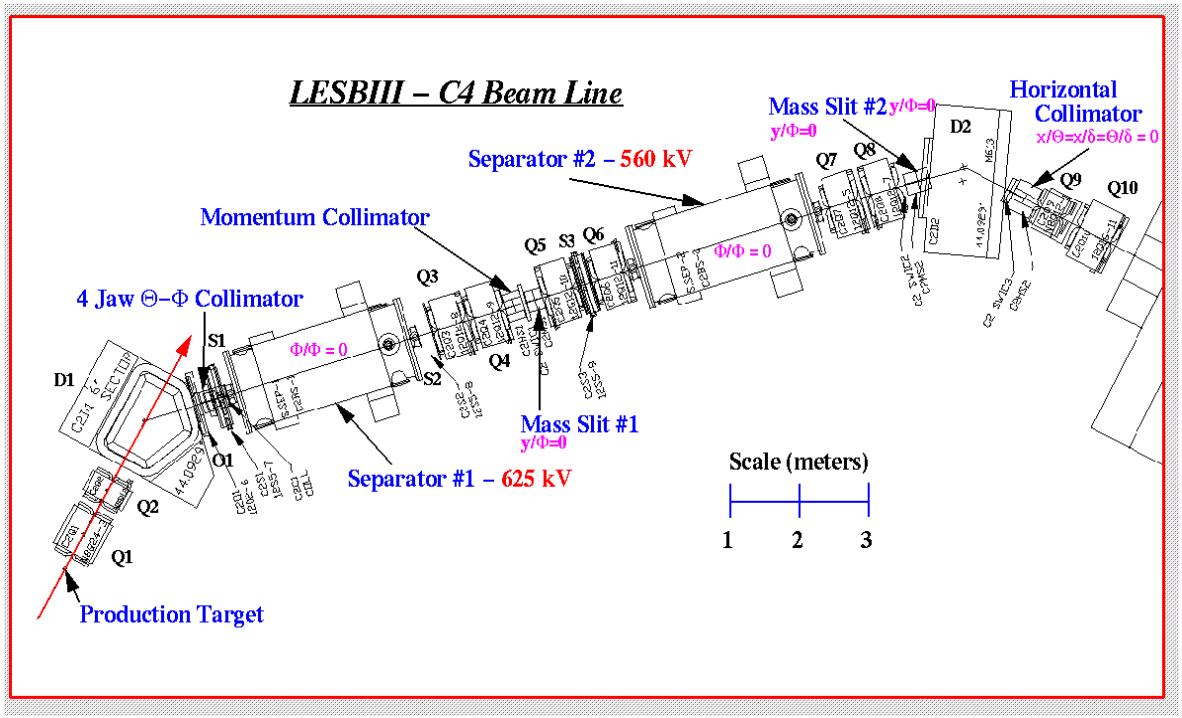
Pt Target before E949 data taking



...and after ($\sim 6 \times 10^{19}$ protons)

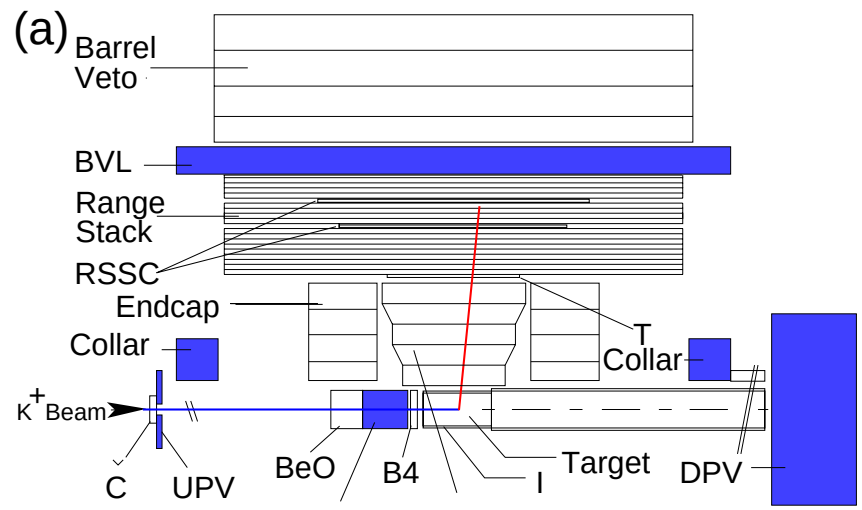


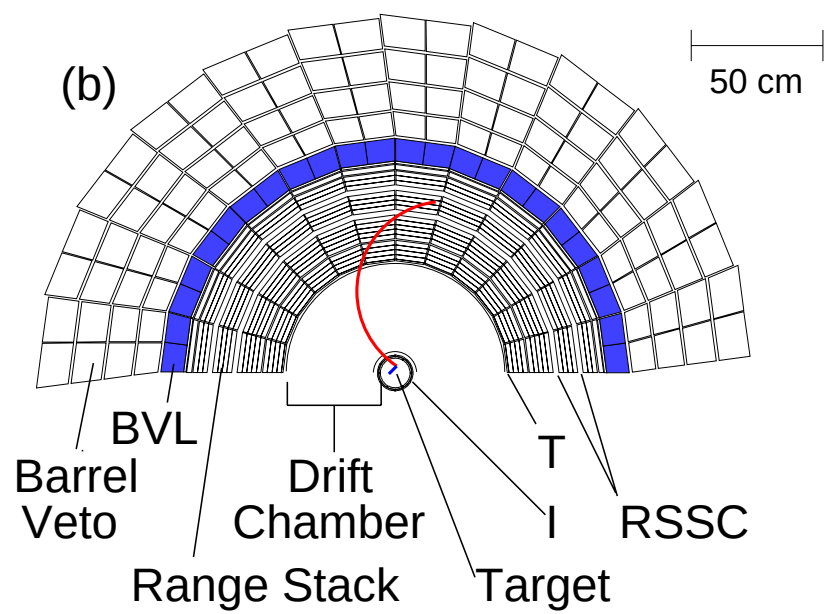


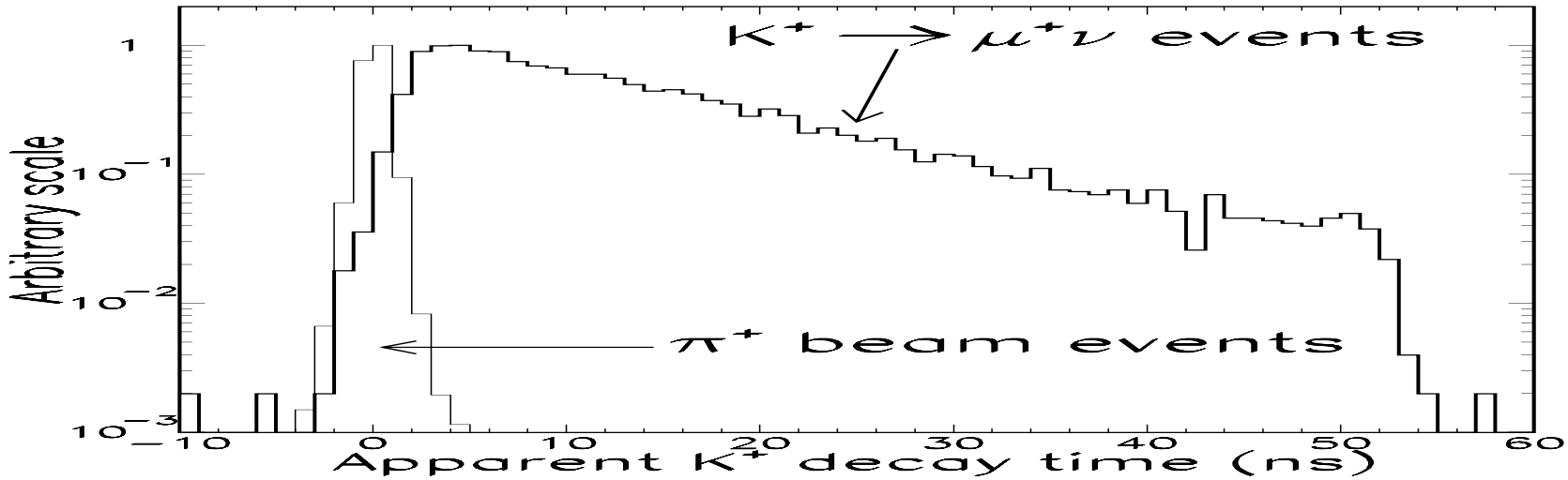


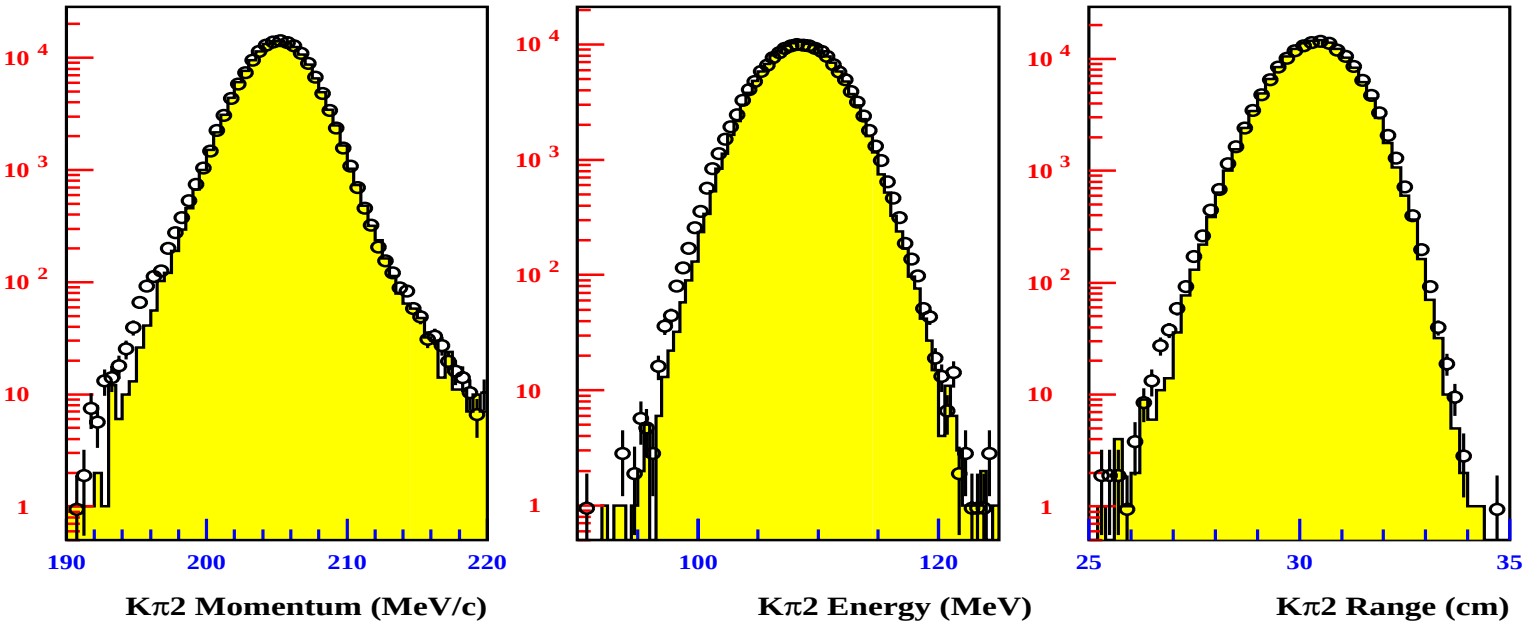
E949 method

- ~ 700 MeV/c K^+ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**



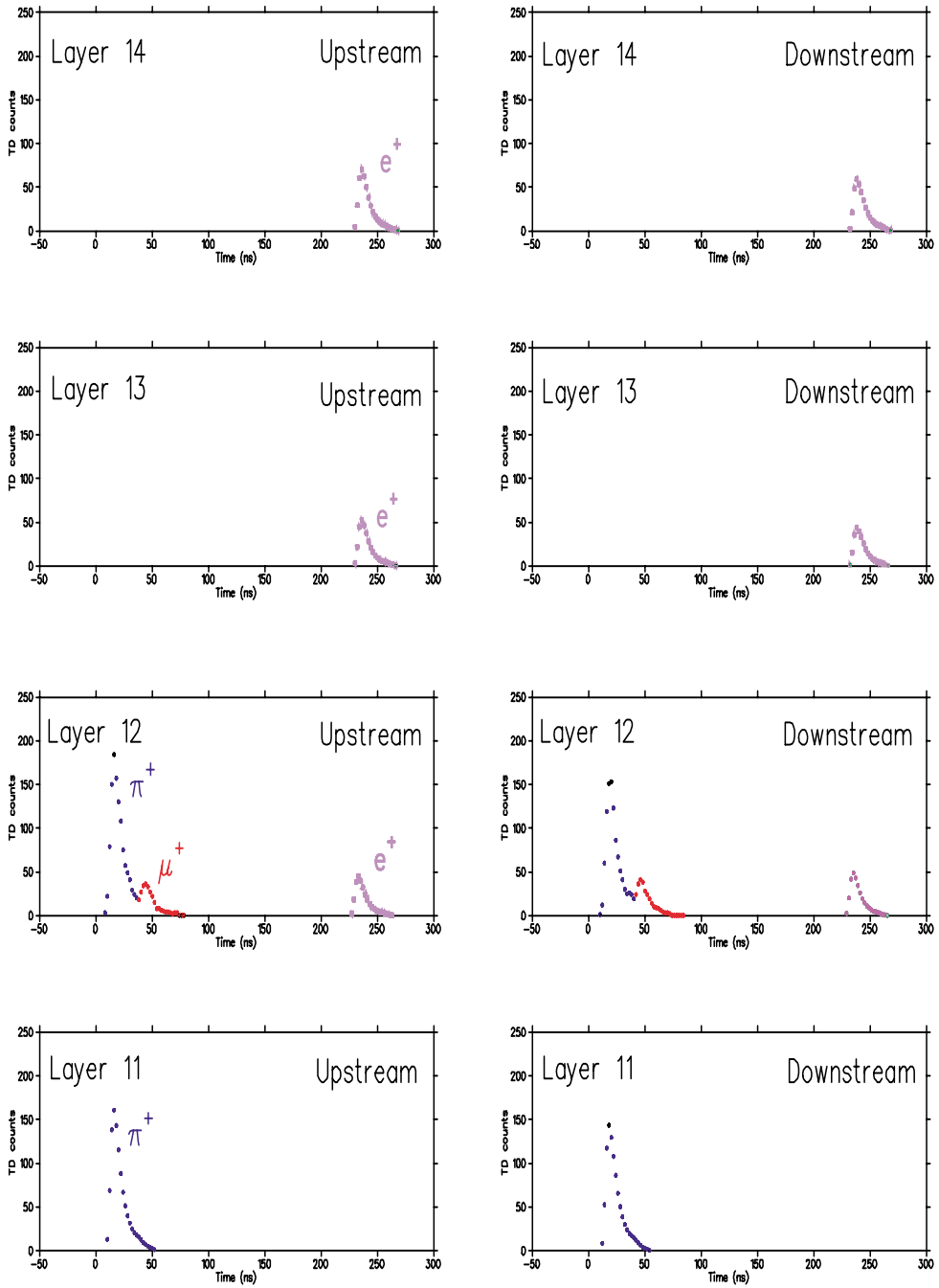






σ_P=2.3 MeV/c σ_E=3.0 MeV σ_R=0.9 cm

E787 (circles), E949 (histogram)



Identify $\pi^+ \to \mu^+ \to e^+$

- Sample pulse height every 2 ns for 2 μs (TDCs to 10 μs)
- π^+ stops in range stack scintillator (2 cm/layer)
- $\pi^+ \to \mu^+\nu$, $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm, $\tau_\pi = 26.0$ ns
- $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, $E_e \leq 53$ MeV, $\tau_\mu = 2.20$ μs

Plots: Pulse height (0 to 250) *vs* time (-50 to 300 ns)

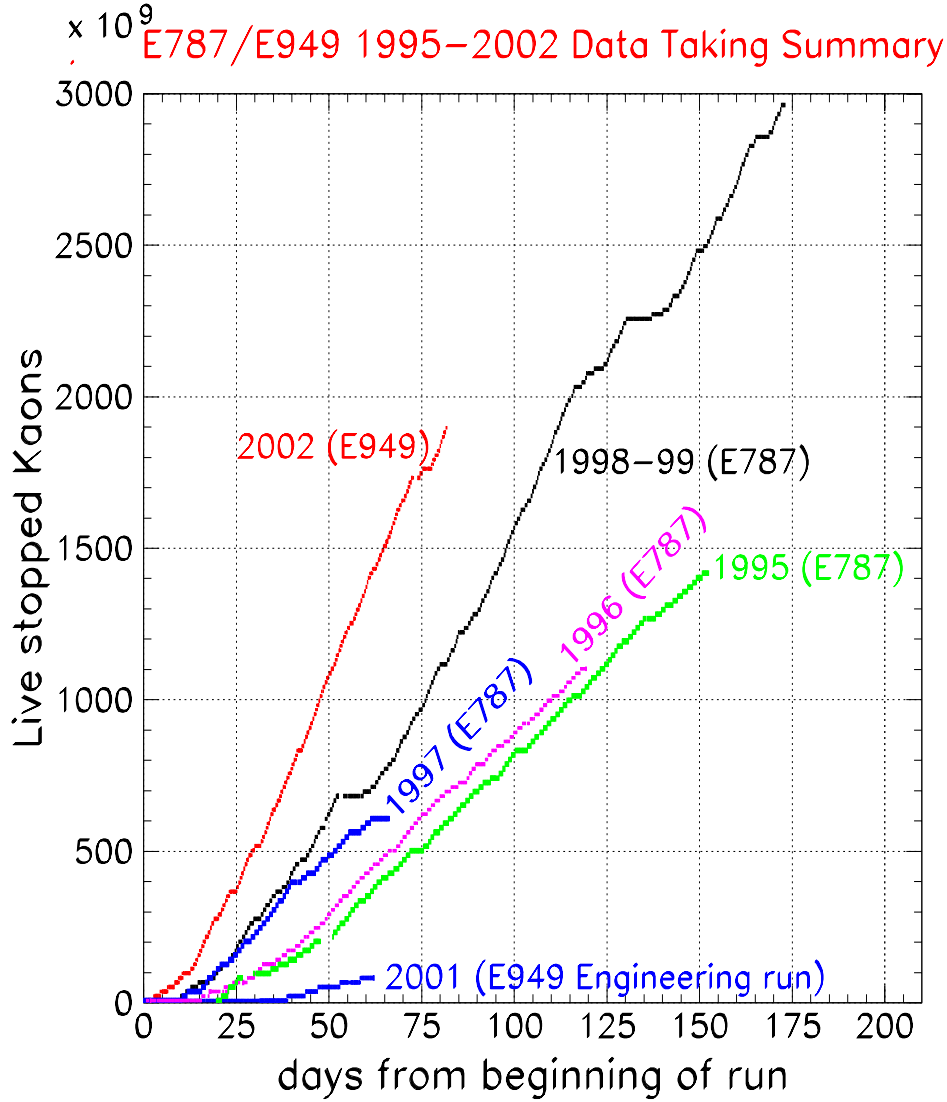
E949 compared with E787

Upgrades to E787:

- More protons from AGS
- Improved photon veto
- Improved tracking and energy resolution
- Higher rate capability due to DAQ, electronics and trigger improvements

Not optimal in 2002:

1. Duty factor.
2. Proton energy.
3. K/π separation.

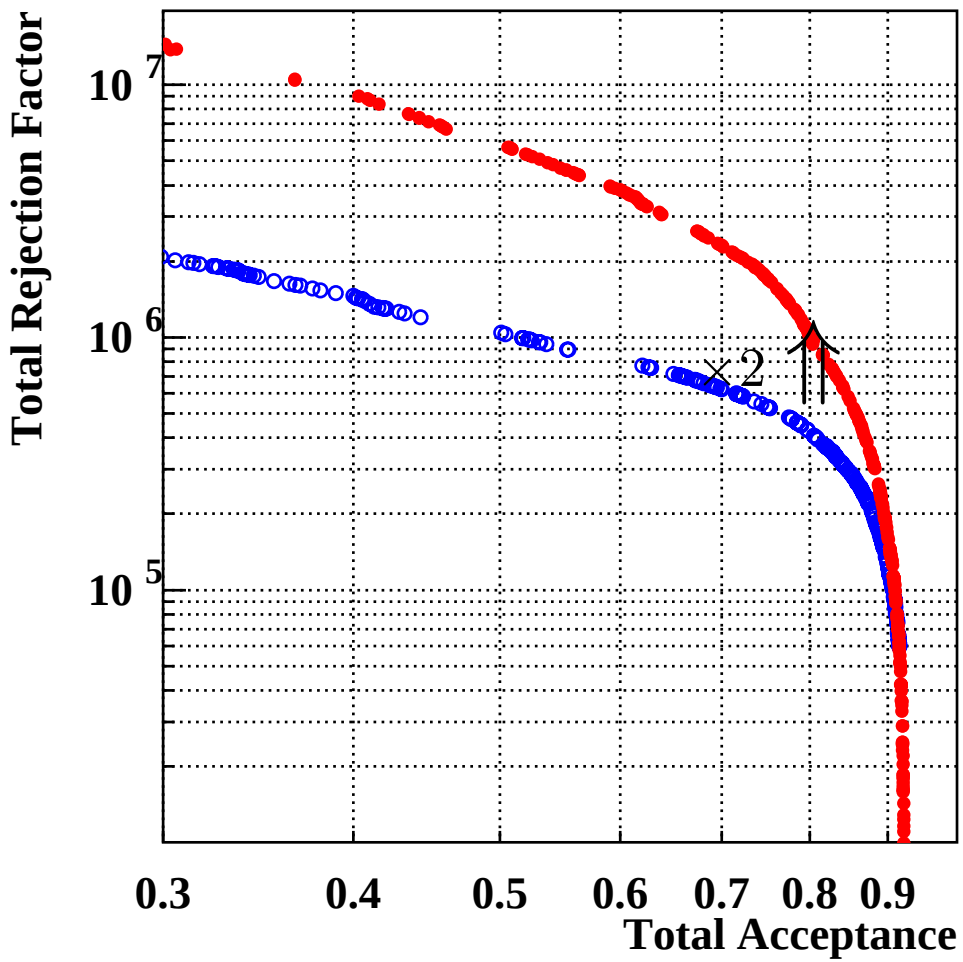


E949: Upgrade of photon veto

Improved photon veto.

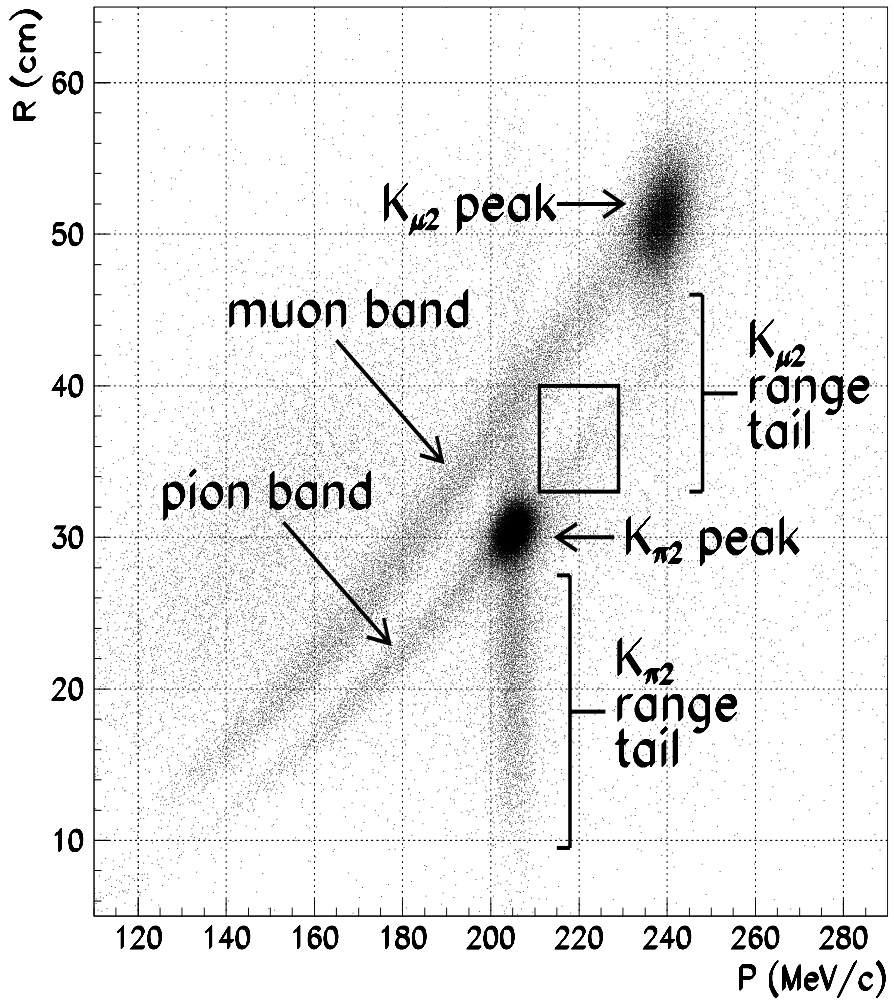
Figure: background **Rejection** as a function of $K^+ \to \pi^+ \nu\bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

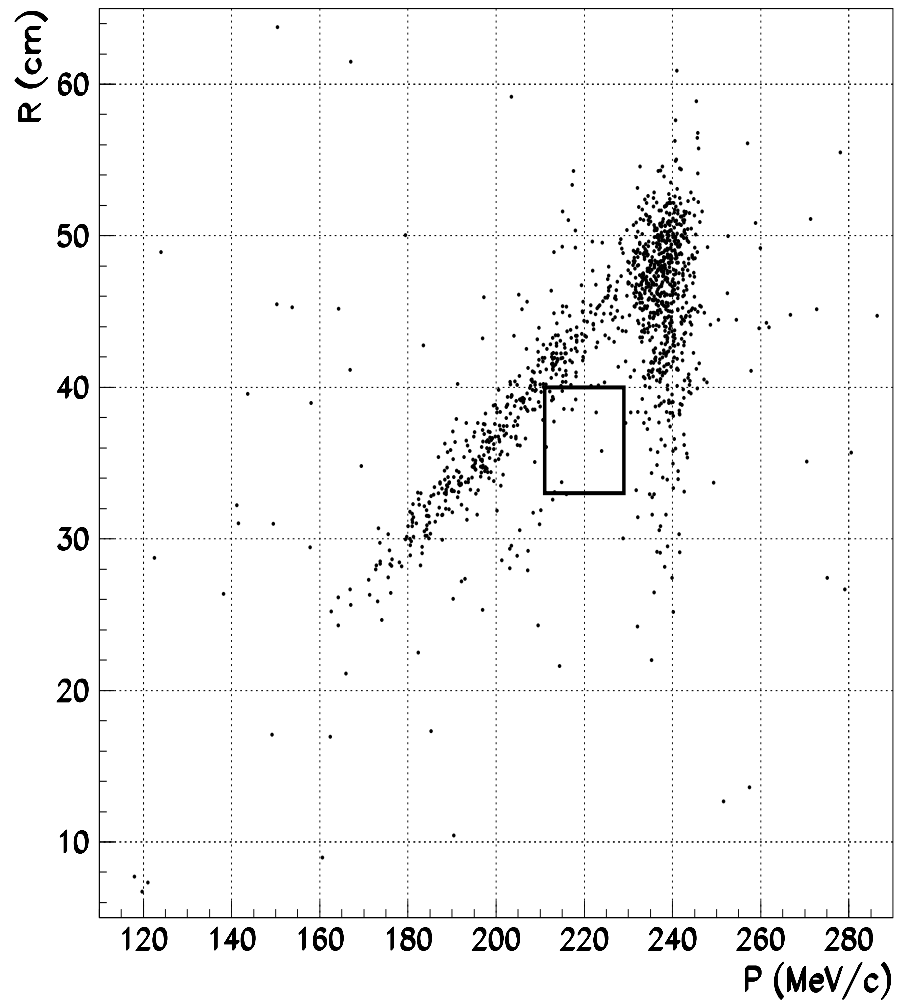
$\sim$ 2$\times$ better rejection at nominal **PNN1** acceptance of 80% *or* $\sim$ 5% more acceptance in E949 with same rejection as E787.



Data

Range (in cm of scintillator) vs. momentum



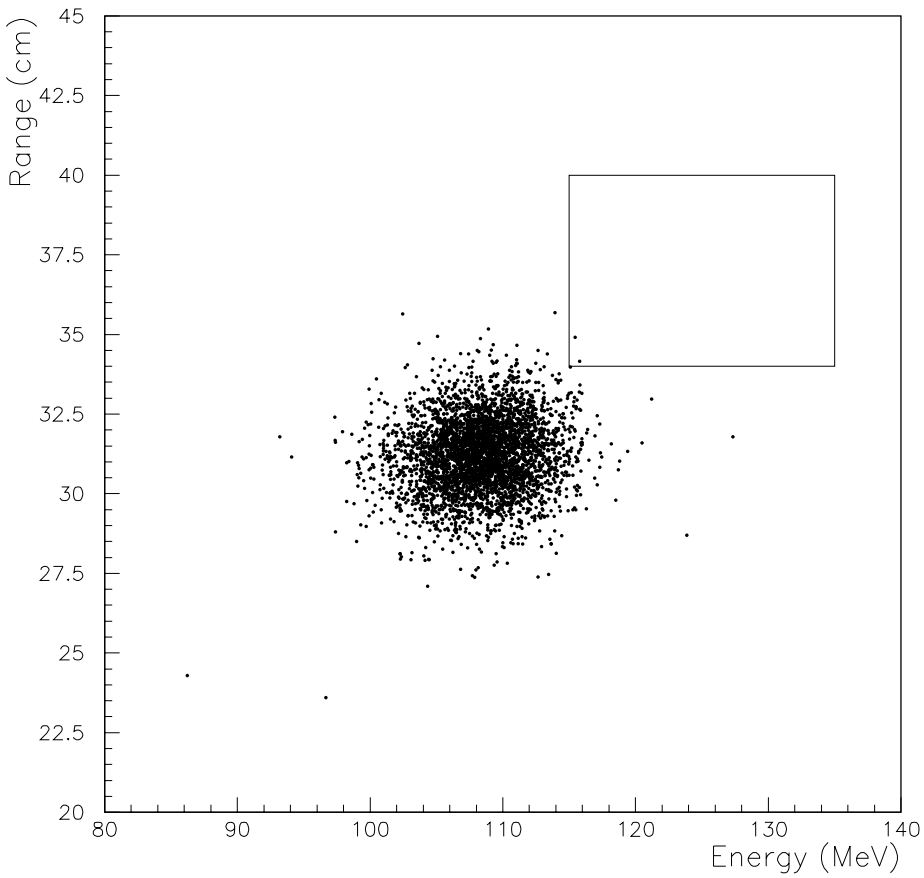


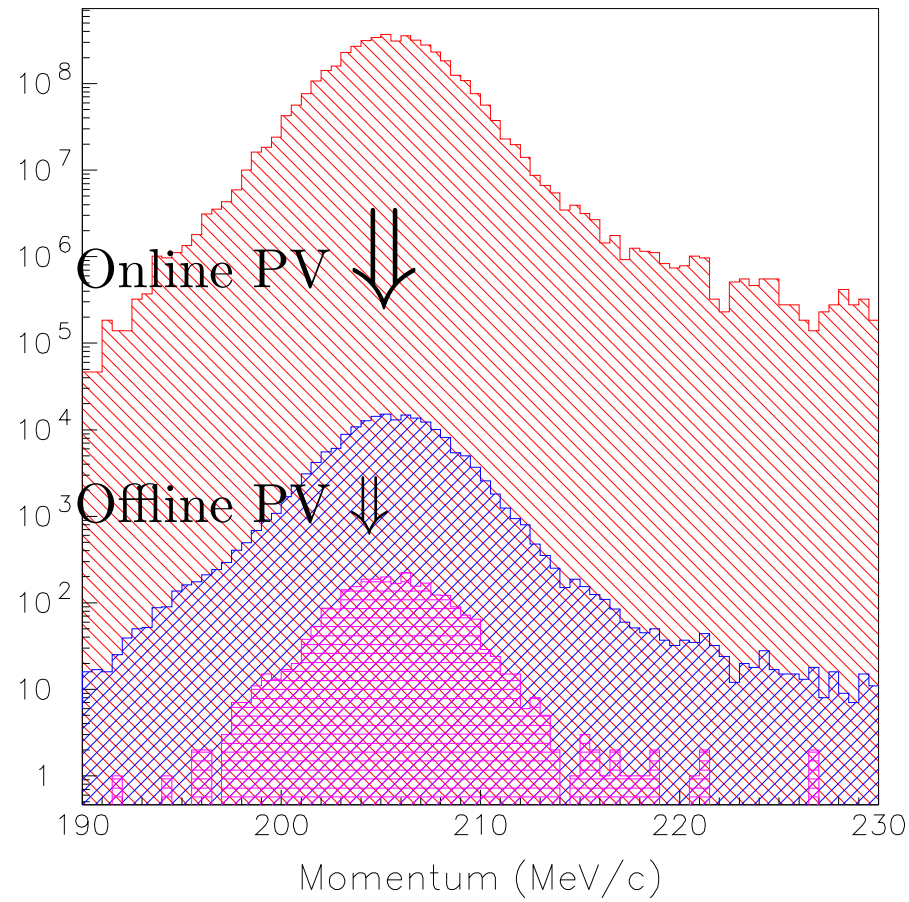
Minimum bias ($K_{\pi 2}$) Trigger **$\pi\nu\bar{\nu}$ Trigger**

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+ \pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

Example: $K^+ \to \pi^+\pi^0$ background rejection





Left: Select photons, measure rejection of kinematic cuts: P, R, E.

Right: Select $K^+ \to \pi^+\pi^0$ kinematically, measure rejection of photon veto. **Photon veto:** Typically 2–9 ns time windows and 0.2–4 MeV energy thresholds ($\bar{\epsilon}_{\pi^\circ} \leq 10^{-6}$)

Verify background prediction by loosening cuts

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

	PV$\times$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$\times$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$\times$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

$K_{\mu m} \equiv K^+ \to \mu^+\nu\gamma$, $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\pi^0$; $\pi^+ \to \mu^+\nu$

TD$\equiv \pi \to \mu \to e$ identification, PV$\equiv$Photon Veto rej., KIN$\equiv$ kinematic rej. $M \times N \equiv$ reduction in rejection with respect to signal region ($\equiv 1\times 1$)

Quantify consistency: Fit $N_{\rm obs} = cN_{\rm pred}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$K_{\pi 2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$K_{\mu 2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$K_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

E949 improved analysis strategy

1. E787 background estimation methods are reliable

2. Divide signal region into cells and calculate background (b_i) and signal acceptance (s_i) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted $K^+ \to \pi^+\pi^0$ background within "signal box"

3. Can calculate $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ using s_i/b_i of any cells containing candidates using likelihood ratio method. (see T. Junk [NIM **A434**, 435 (1999)])

4. Increase total size of signal region to increase acceptance at cost of more total background

S:N-ordered cell construction

Construction of cells from 'background functions':

- γ veto timing windows/energy thresholds (PV)
- Proximity (E, P, R) to $K_{\pi 2}$ peak (Kp2)
- $\pi \to \mu \to e$ properties via NN function (TD)
- Proximity (P) to $K_{\mu 2}$ "tail" (Km2t)
- Proximity (R,P) to $K_{\mu 2}$ "band" (Km2b)
- Kaon lifetime, or "delayed coincidence" (bm1)
- 2nd-hit timing in beam wire chambers (bm2)

Sample functions at discrete points to form a grid of 'cells'; calculate (absolute) background levels (b_i) and (relative) signal acceptance (s_i) in each cell.

- 1995–97: divide signal region into 2 cells
- 1998: divide signal region into 486 cells
- 2002: divide signal region into 3781 cells

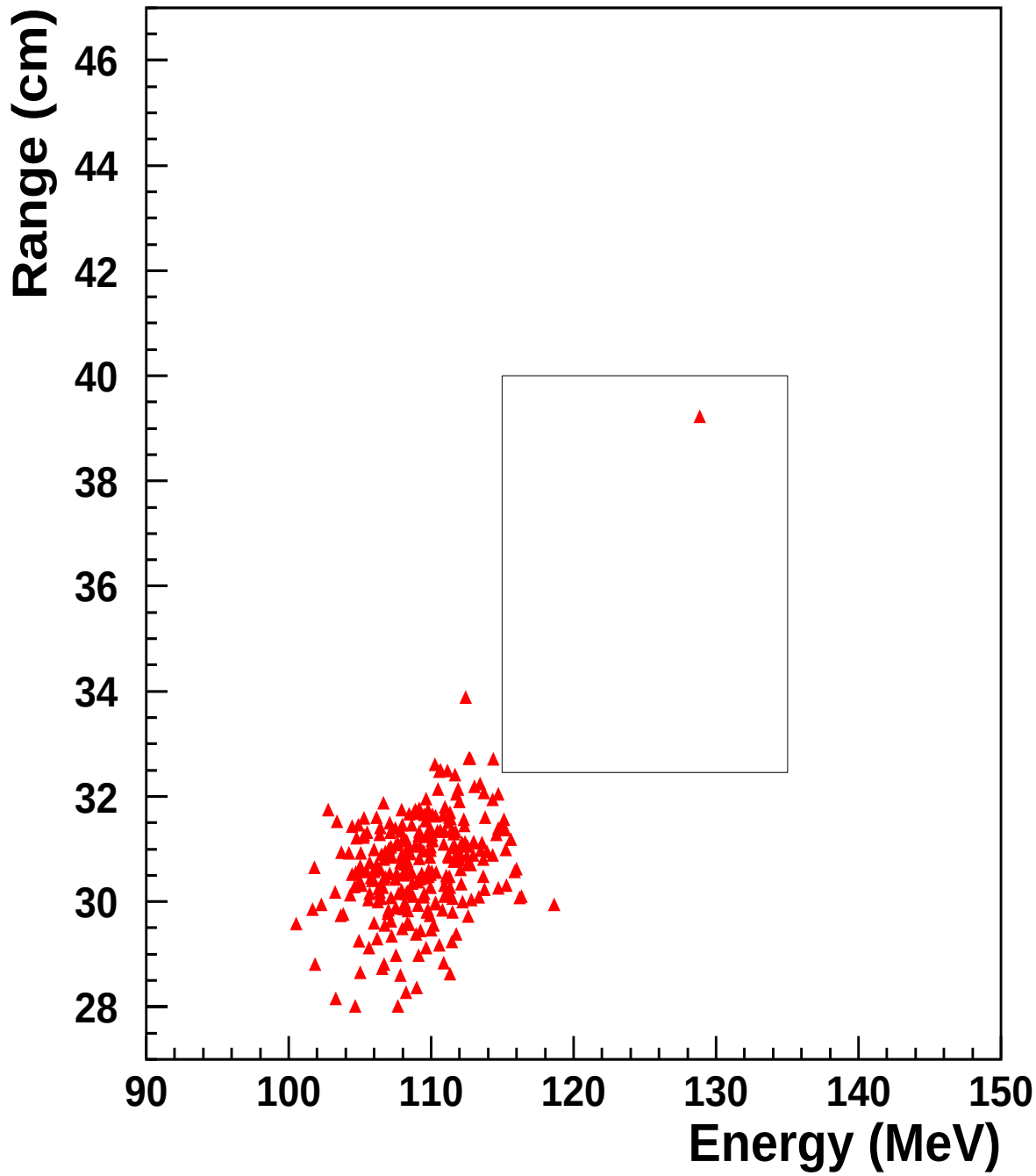
Opening the box

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

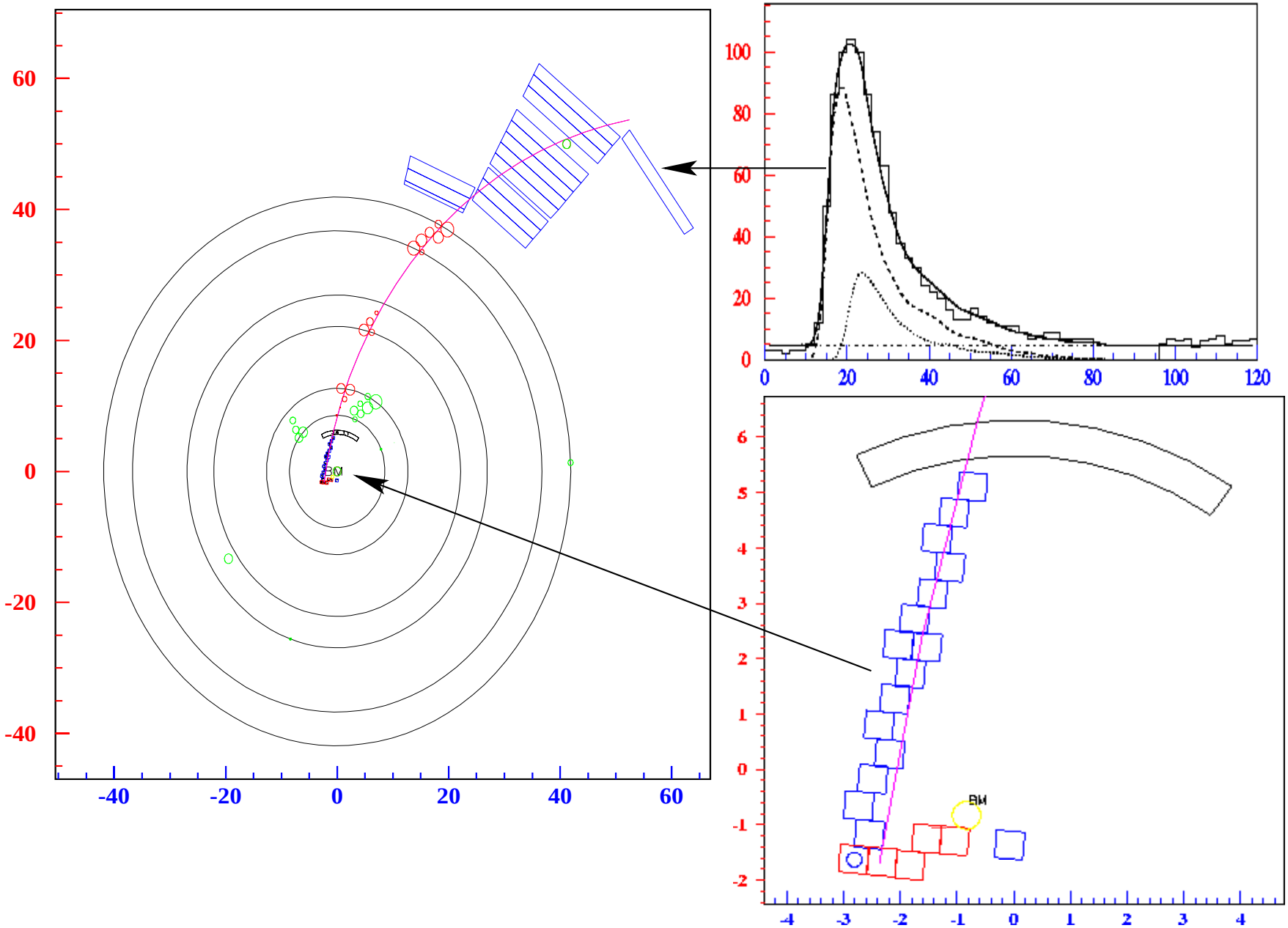
Solid line shows signal region.

Single candidate found.

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



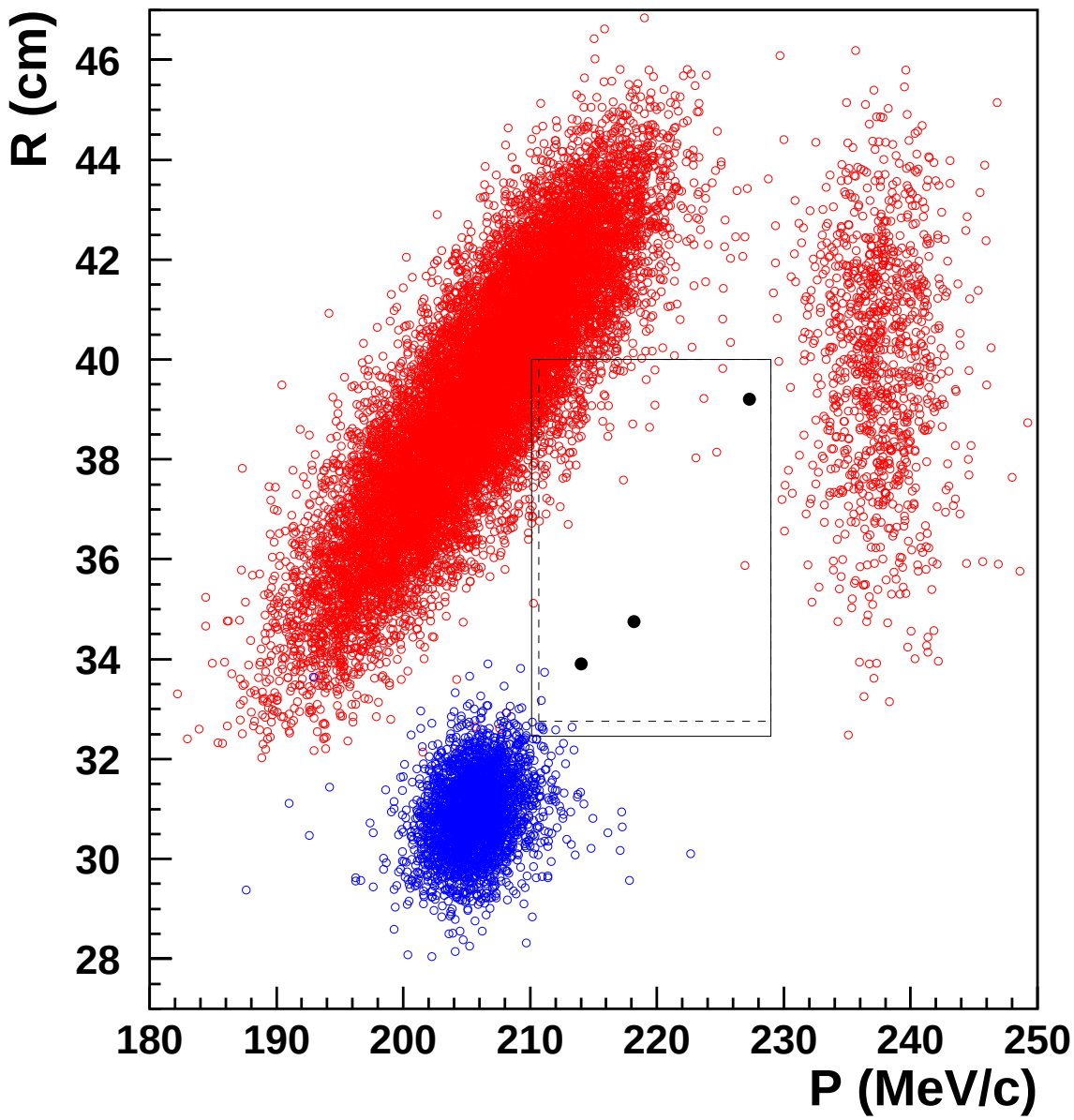
Event display



some details

Date of event	April 2, 2002 (1017778112 uut)
Tape/run/spill/event	30266.3.2/48634/335/76046
Time in spill	1.27s
Kaon energy in target	79.7 MeV
Kaon time in target (t_K)	0.6 ns
z of kaon decay vertex	8.9 cm
(x, y) of kaon decay vertex	(-2.8, -1.6) cm
Pion energy in target	20.8 MeV
Pion range in target	7.6 cm
Pion time in target (t_π)	4.9 ns
Pion time in IC (ictime)	3.8 ns
$\cos\theta$ of the pion track	-0.24
ϕ_0 of the pion track	1.42
Total momentum of pion track	227.3 MeV/c
Total range of pion track	39.2 cm
Total kinetic energy of pion track	128.9 MeV
RS stopping sector/layer	3/14
Pion lifetime	6.2 ns
Muon energy	3.7 MeV
Muon lifetime	1370.53 ns
Range-momentum	0.63

Anything worrisome nearby?



- **black points** are E787+E949 data with all cuts
- **blue points** are E949 γ-tagged data
- **red points** are E949 μ^+-tagged data (no $\pi^+ \rightarrow \mu^+$ decay)

Are these events background?

How likely is it that the candidate is due to known background?

Question: Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

Answer: ~ 7

The sum of background in all cells with s_i/b_i greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ($\sim 7/100$).

The E949 candidate is more likely to be due to background than the two E787 candidates.

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

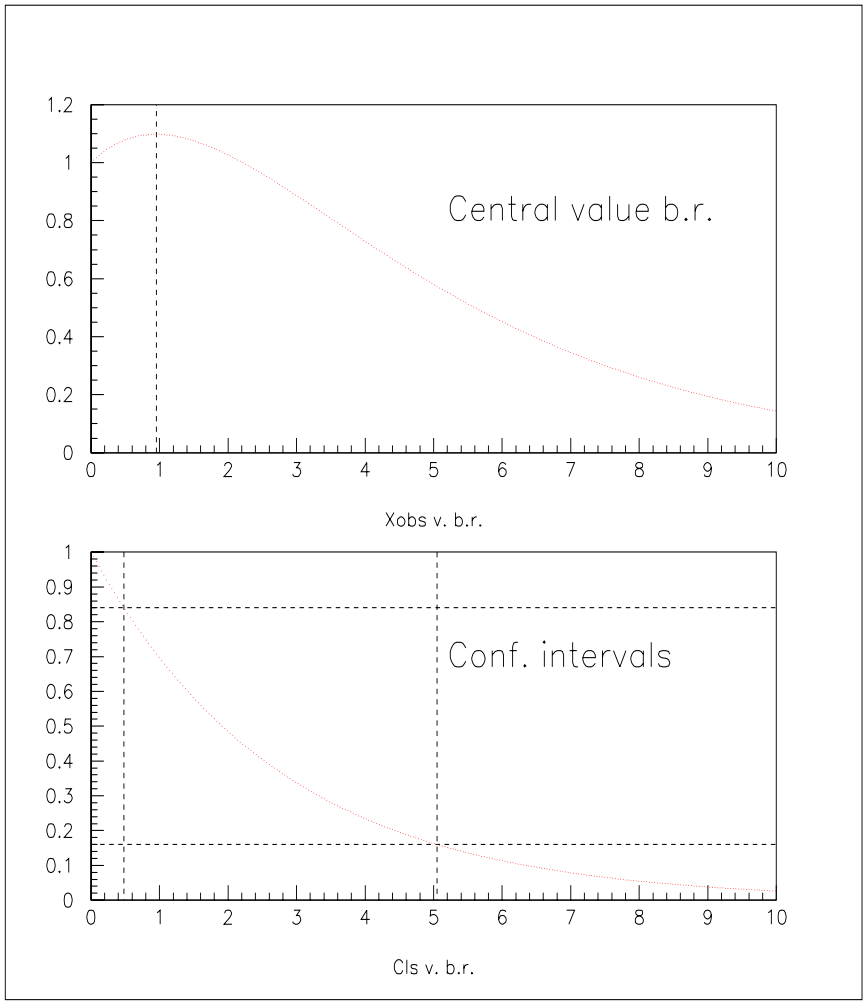
Branching ratio and confidence limits

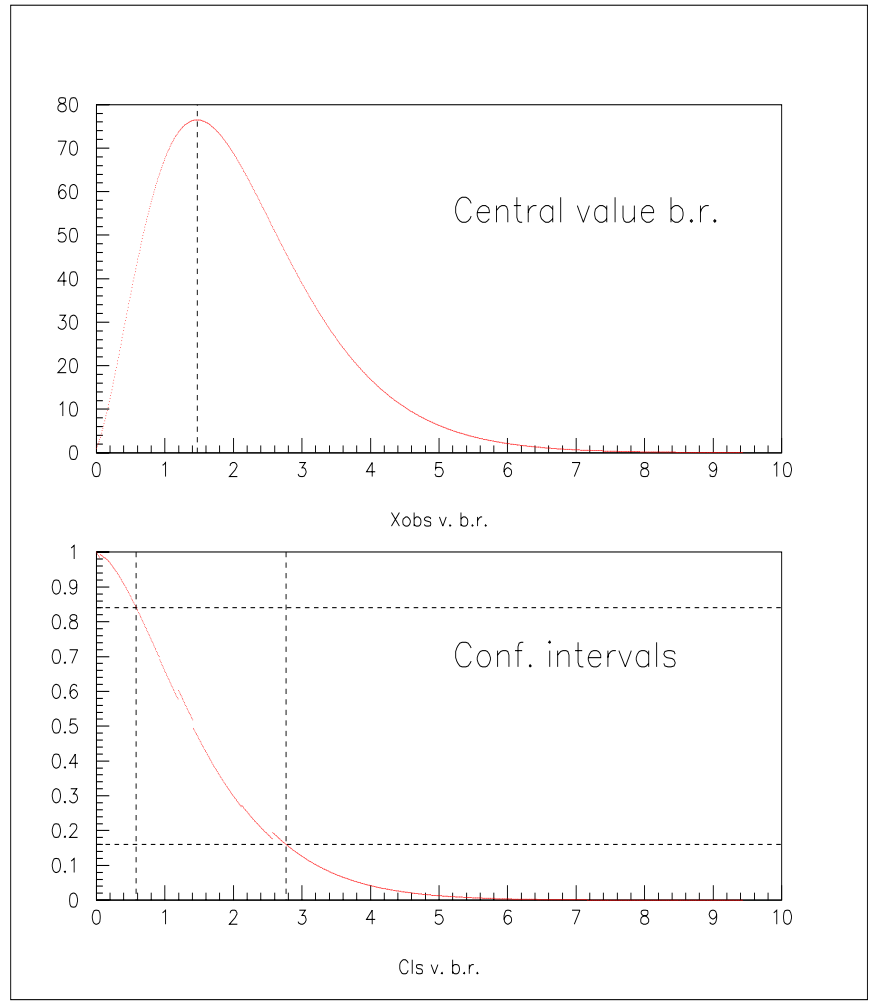
2002 candidate event alone

- Branching ratio: $(0.96^{+4.09}_{-0.47}) \times 10^{-10}$
- $1 - CL_b$: 0.074

Combined measurement (1995–2002)

- Combined BR: $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$
- Combined $1 - CL_b$: 0.001



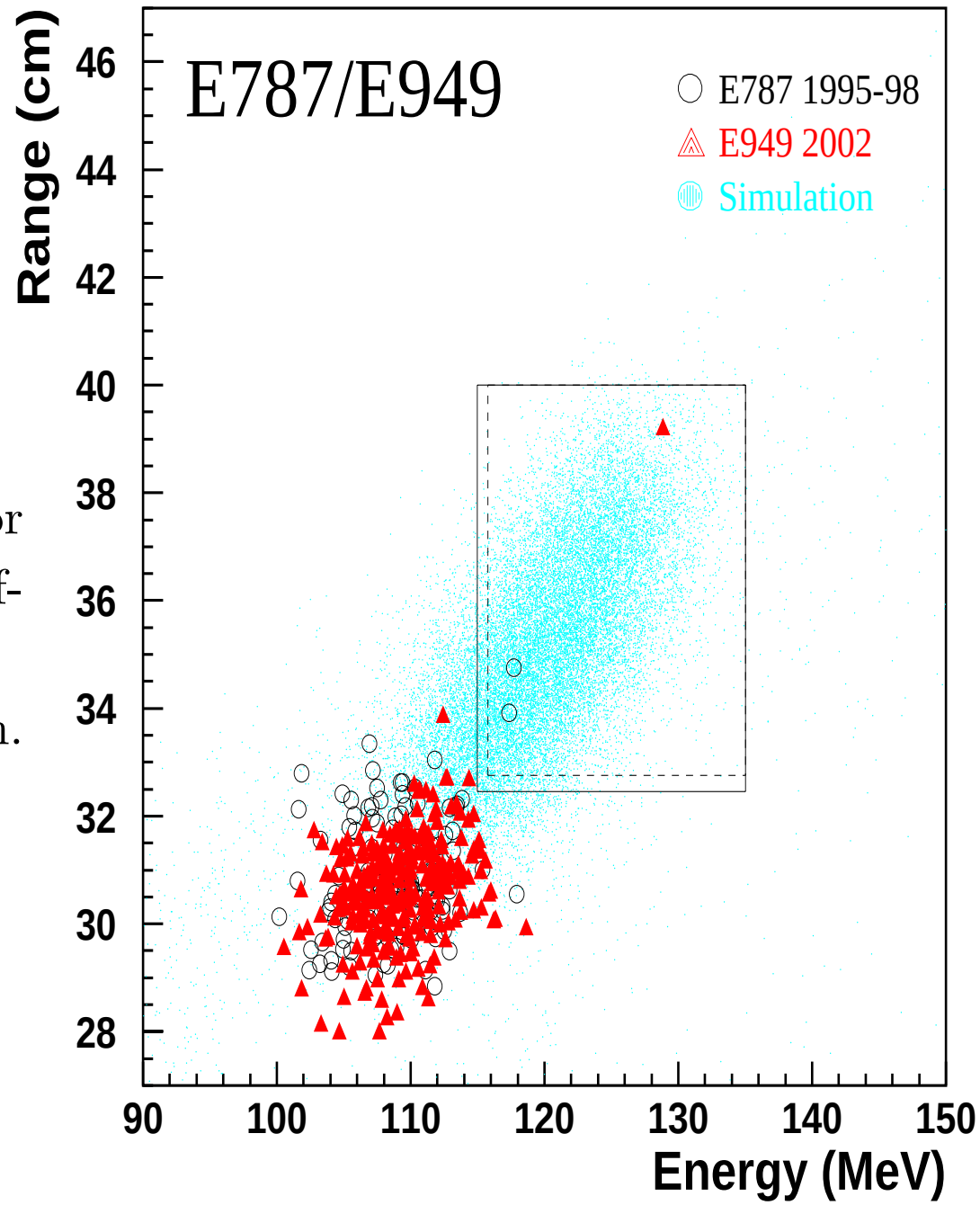


Combined E787/E949

Range (cm) *vs.* Energy (MeV) for combined E787 and E949 data after all other cuts applied.

Dashed line is E787 signal region.

Solid line is E949 signal region.



1995–2002: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}\ ) = \mathbf{1.47}^{+1.30}_{-0.89} \times 10^{-10}$

	E787		E949
Stopped K$^+$ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

b_i = background of cell containing candidate

$S_i \equiv \mathcal{B} A_i N_K$ = signal for cell containing candidate

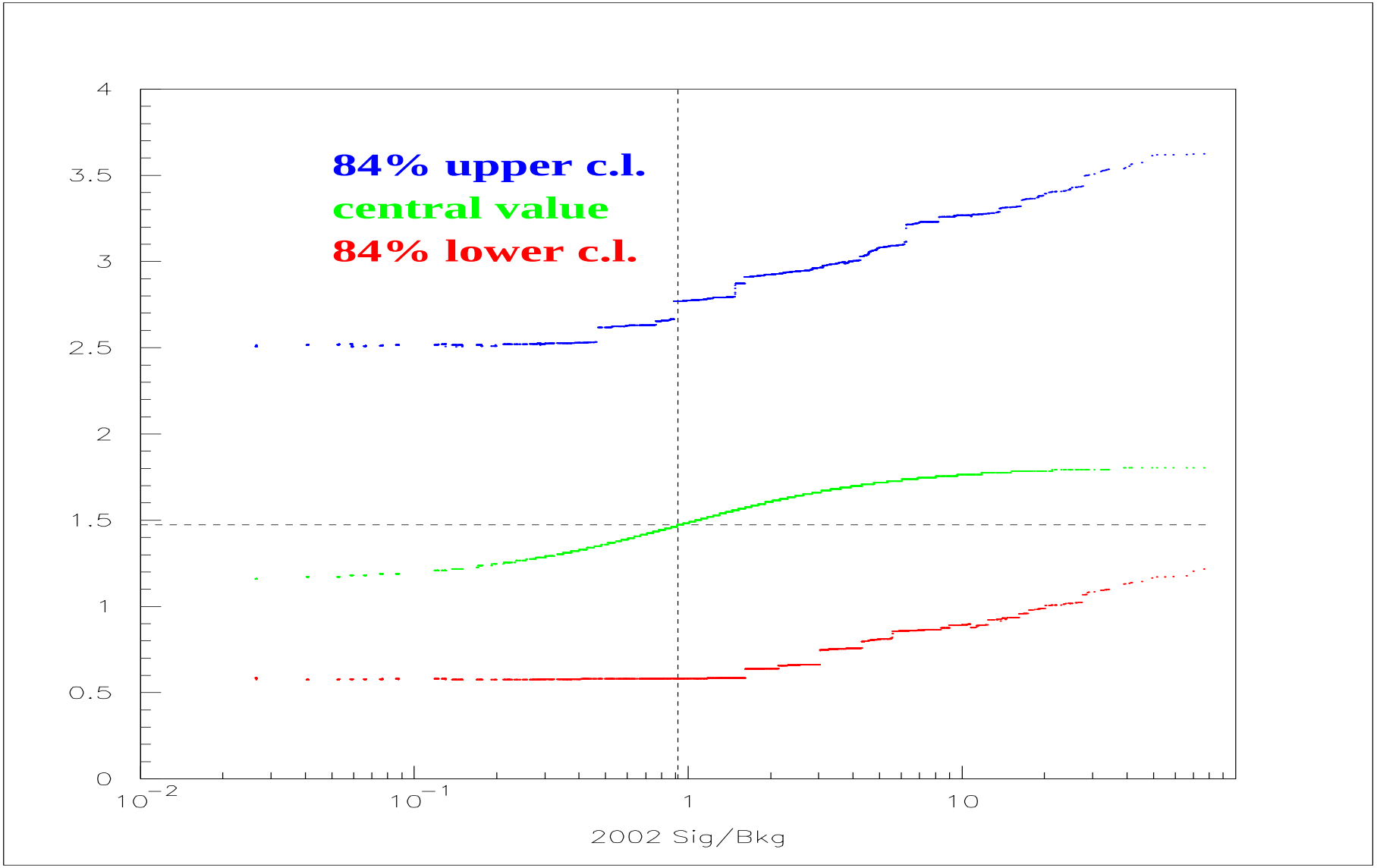
$A_i \equiv$ acceptance

$\mathcal{B}$ = measured central value of K$^+ \to \pi^+ \nu\bar{\nu}$ branching fraction

$W_i \equiv S_i/(S_i + b_i)$ = *a posteriori* event weight

Dependence on S/B

Branching ratio (10^{-10}) vs. S/N of each cell.



MC simulation of one event in different S/N cells of the E949 2002 data set.

Combined E787 and E949 results for $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$

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

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

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) < 3.22 \times 10^{-10}$ at 90% CL.

SM prediction†: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

$\mathcal{B}(\mathrm{K_L} \to \pi^\circ\nu\bar{\nu}) < 1.4 \times 10^{-9}$ at 90% CL. [Grossman&Nir PL**B398**,163(1997)]

$0.0055 < |V_{td}| < 0.0271$

$|Im\lambda_t| < 0.91 \times 10^{-3}$

$-0.79 \times 10^{-3} < Re\lambda_t < 1.08 \times 10^{-3}$

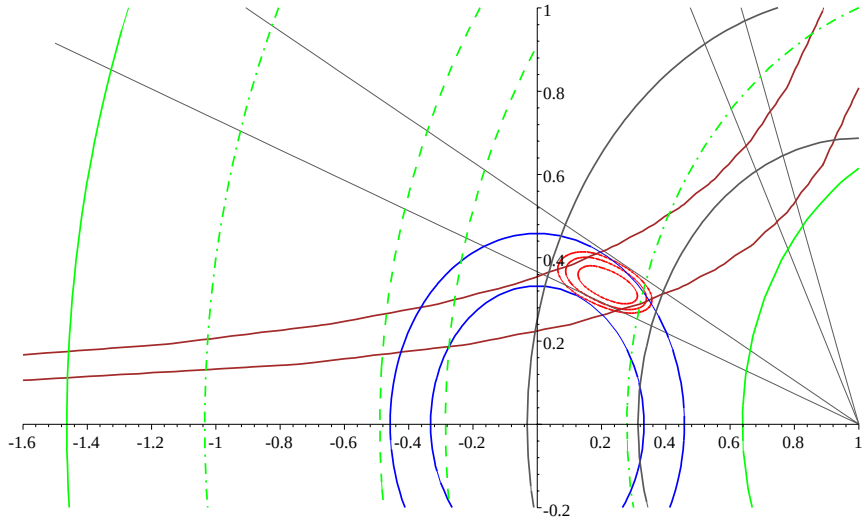
$0.24 \times 10^{-3} < |\lambda_t| < 1.08 \times 10^{-3}$

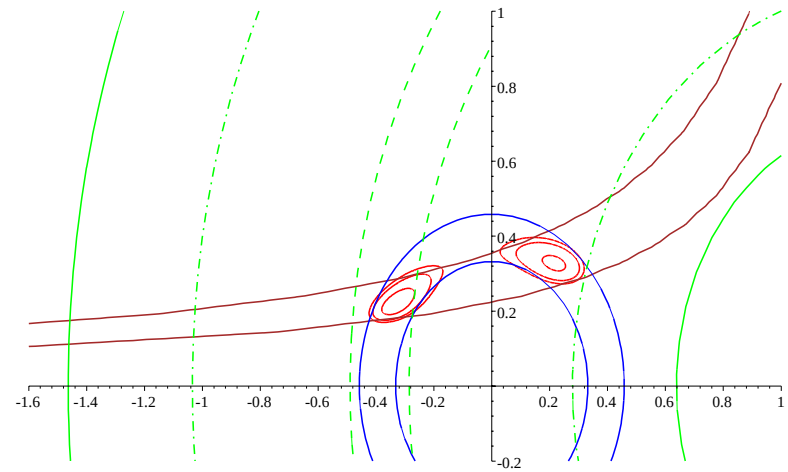
E787 result: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

† Reference: Buchalla& Buras, NP**B548** 309 (1999);

Isidori, hep-ph/0307014;Buras, hep-ph/0402112 ; Kettell, Landsberg & Nguyen, hep-ph/0212321

$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ and the Unitarity Triangle



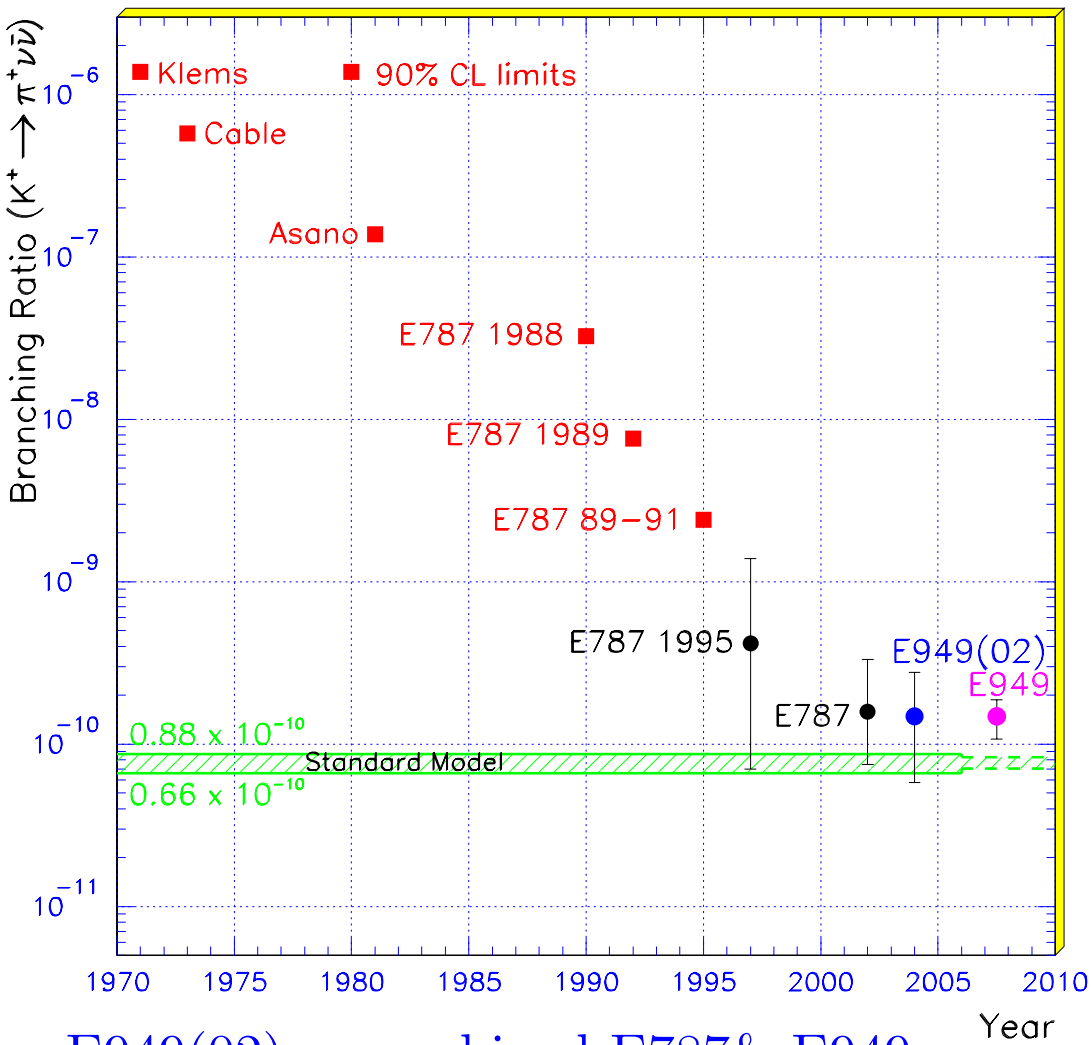


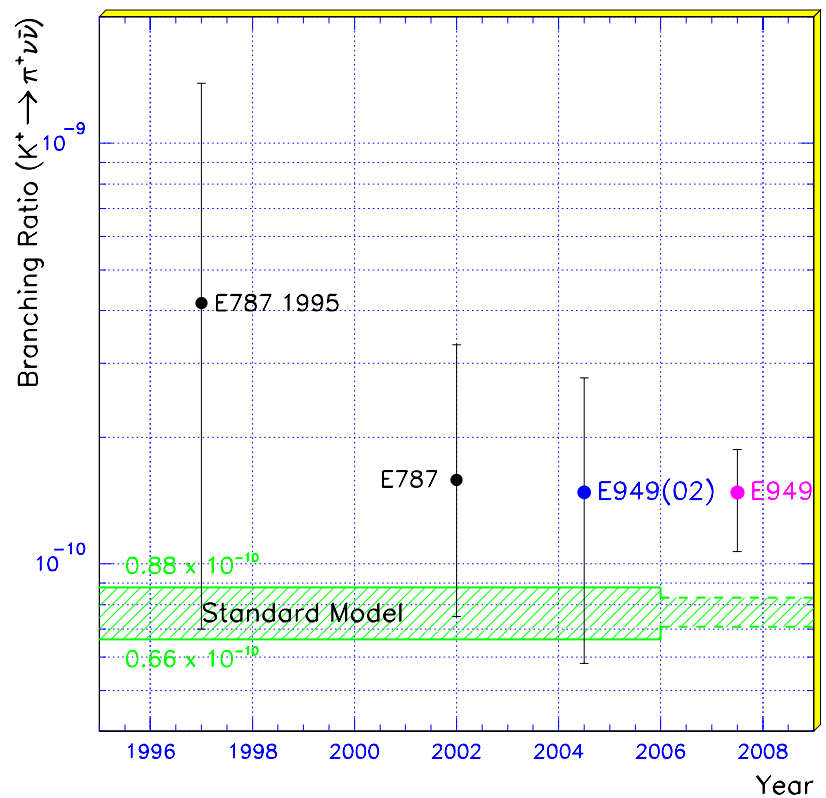
Green lines show $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ (with theoretical uncertainty): central value (dashed), 68% interval (dot-dash), 90% interval (solid).

Red ovals show 68%, 90% and 95% areas from other measurements ($|V_{ub}|$, ϵ_K, [right figure does not include] $\sin 2\beta$, Δm_d, $\Delta m_s/\Delta m_d$, which all depend on B_d mixing)

Provided by Gino Isidori.

Progress in $K^+ \to \pi^+ \nu\bar{\nu}$





Narrowing of "SM prediction" assumes measurement of B_s mixing consistent with prediction.

E949(02) = combined E787& E949.

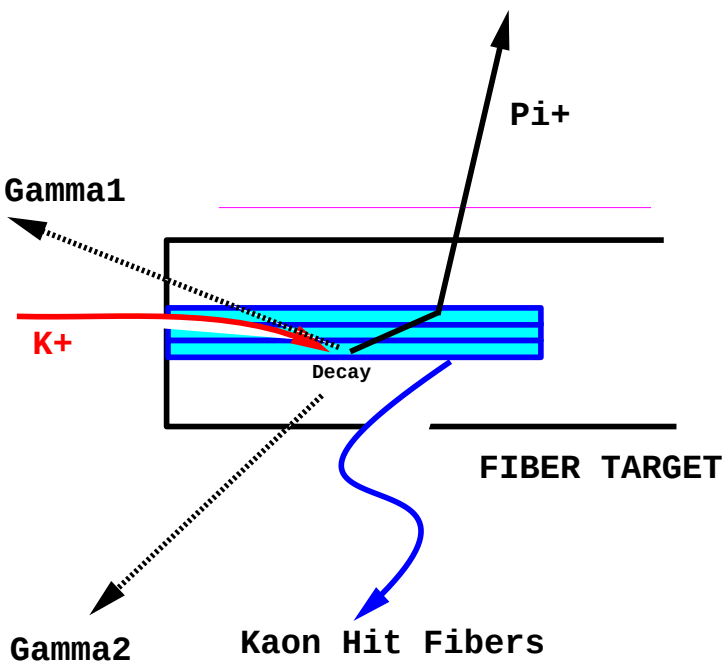
E949 projection with full running period.

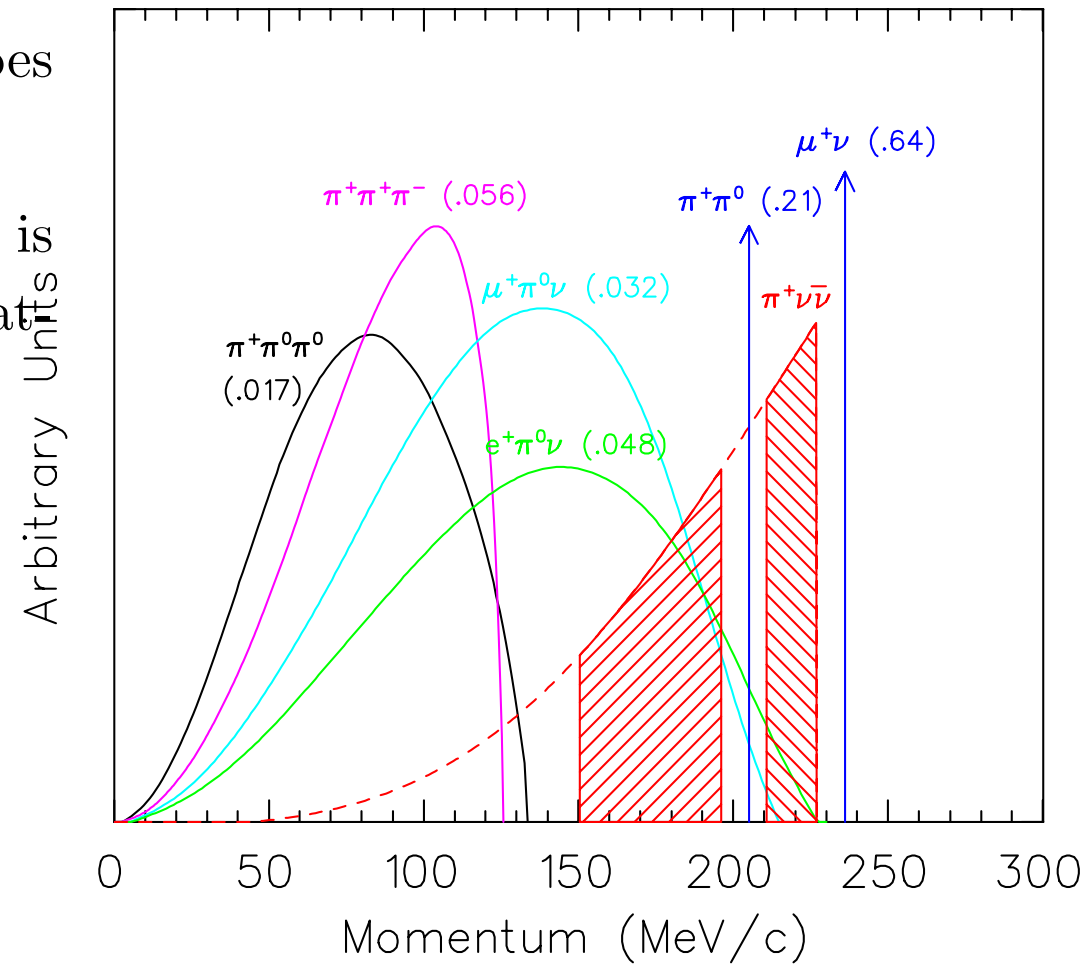
Very interesting .... so What Next?

- A 3rd $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ event has been observed. The BR remains 2×SM, but consistent with it.
  $\Longrightarrow$ **More data is needed.**
- E949 is analyzing more data (PNN2, phase space below the $K^+ \rightarrow \pi^+ \pi^\circ$ peak)
- More E949 running?
- Next generation $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ experiment?

PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

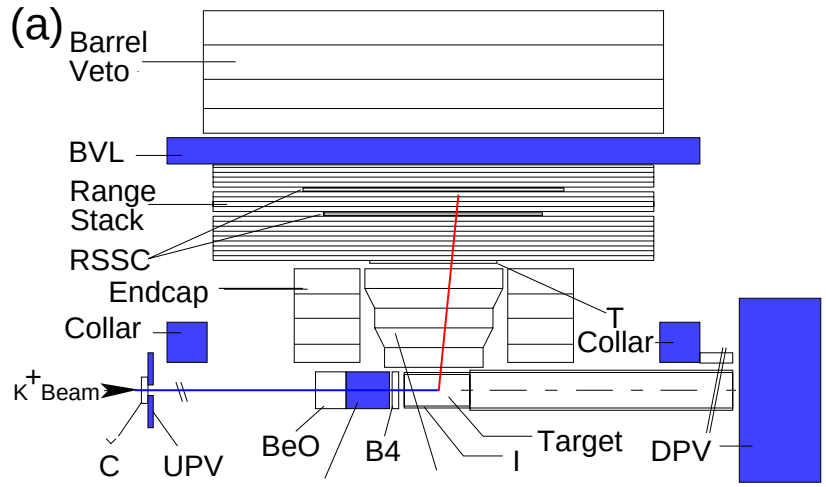
- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

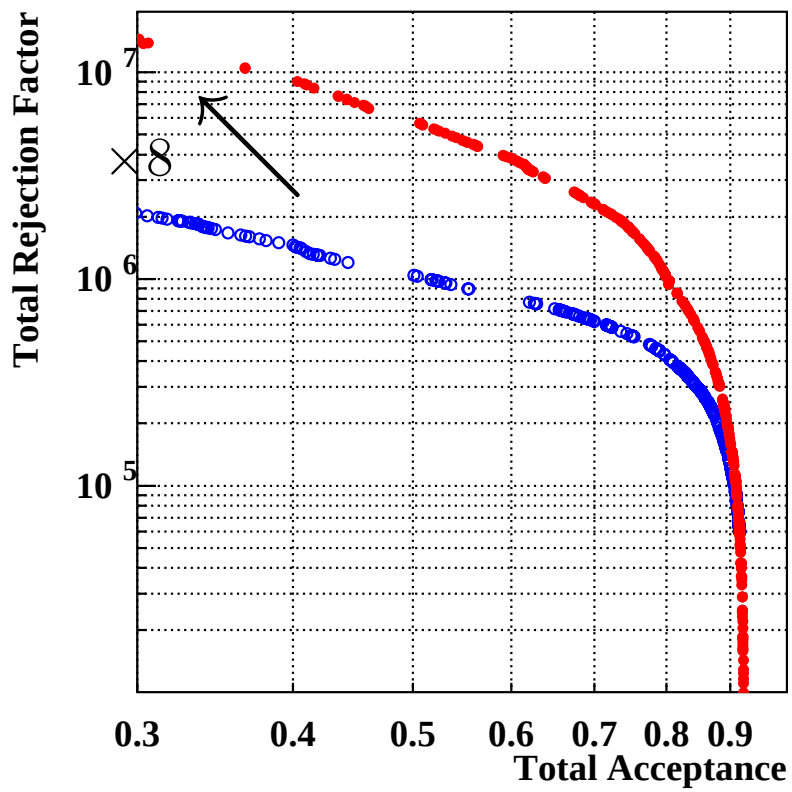




E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with S/B = 1. This implies ×2 increase in acceptance and ×5 increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify $K^+ \rightarrow \pi^+\pi^0$ followed by π^+ scatter in target.





What about more running of E949

• BNL and FNAL developed a plan to fully exploit the 'kaon' component of flavor physics and to capitalize on the observation of $K^+ \to \pi^+ \nu \overline{\nu}$ by E787. This plan included E949, designed to observe 10 SM events, and CKM, using a new decay-in-flight technique with higher rate capability, designed to observe 100 SM events.

• E949 was evaluated as 'must do' by the BNL PAC and approved by BNL; CKM was later given scientific approval by FNAL.

• This plan was endorsed by DOE-HEP and E949 was approved in August 1999 to run for 60 weeks, concurrent with RHIC operation, over three years (FY01–03).

• HEP operations at AGS halted for FY03 after 12 weeks of successfull running. Upgrades performed as predicted.

• A proposal to continue running E949 has been submitted to the National Science Foundation

The future of $K^+ \to \pi^+ \nu \bar{\nu}$

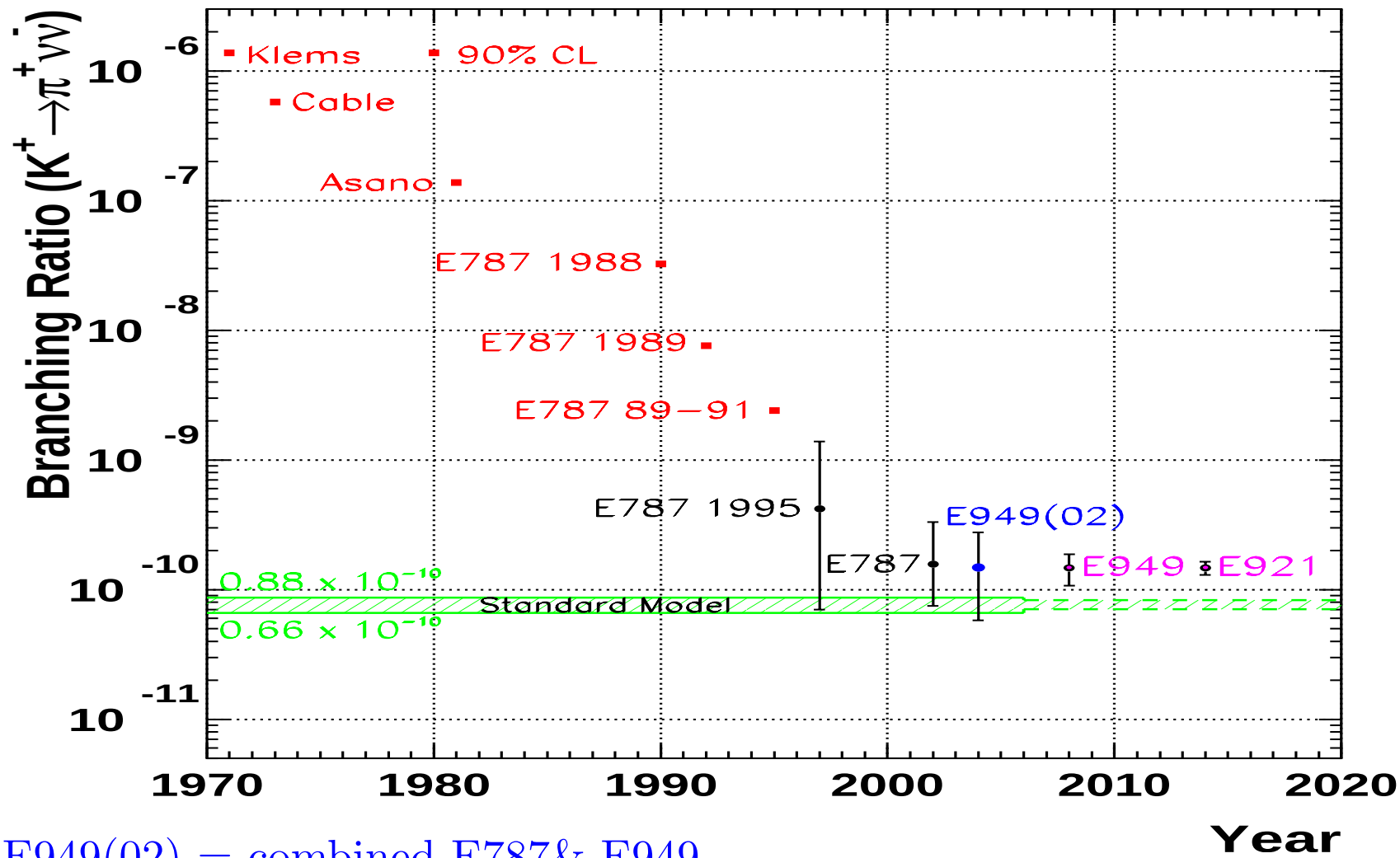
- E949 Analysis of $K^+ \to \pi^+ \nu \bar{\nu}$ for $P(\pi^+) < 195$ MeV/c is in progress.

- The E949 detector and collaboration are ready to complete the experiment and are awaiting funding.

- CKM has scientific approval from FNAL — but budgetary disapproval from P5. A more cost effective version is under development.

- ...and if the US wants to cede leadership in this field: another stopped-K^+ experiment to measure $K^+ \to \pi^+ \nu \bar{\nu}$ is under consideration at J-PARC in Japan and a K^+ decay-in-flight experiment is under consideration at CERN.

Further Progress in $K^+ \to \pi^+ \nu\bar{\nu}$?



E949(02) = combined E787& E949.

E949 projection with full running period.

FNAL-E921 projection with full running period.

Conclusions

- Upgrades of E787 to create E949 were successful.
- E949 has observed an additional $K^+ \to \pi^+\nu\bar{\nu}$ candidate and measures $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$. This result is twice the SM prediction, although consistent with it.
- The detector and collaboration are ready to complete the experiment.
- E949 analysis of $K^+ \to \pi^+\nu\bar{\nu}$ for $P(\pi^+) < 195$ MeV/c is in progress.

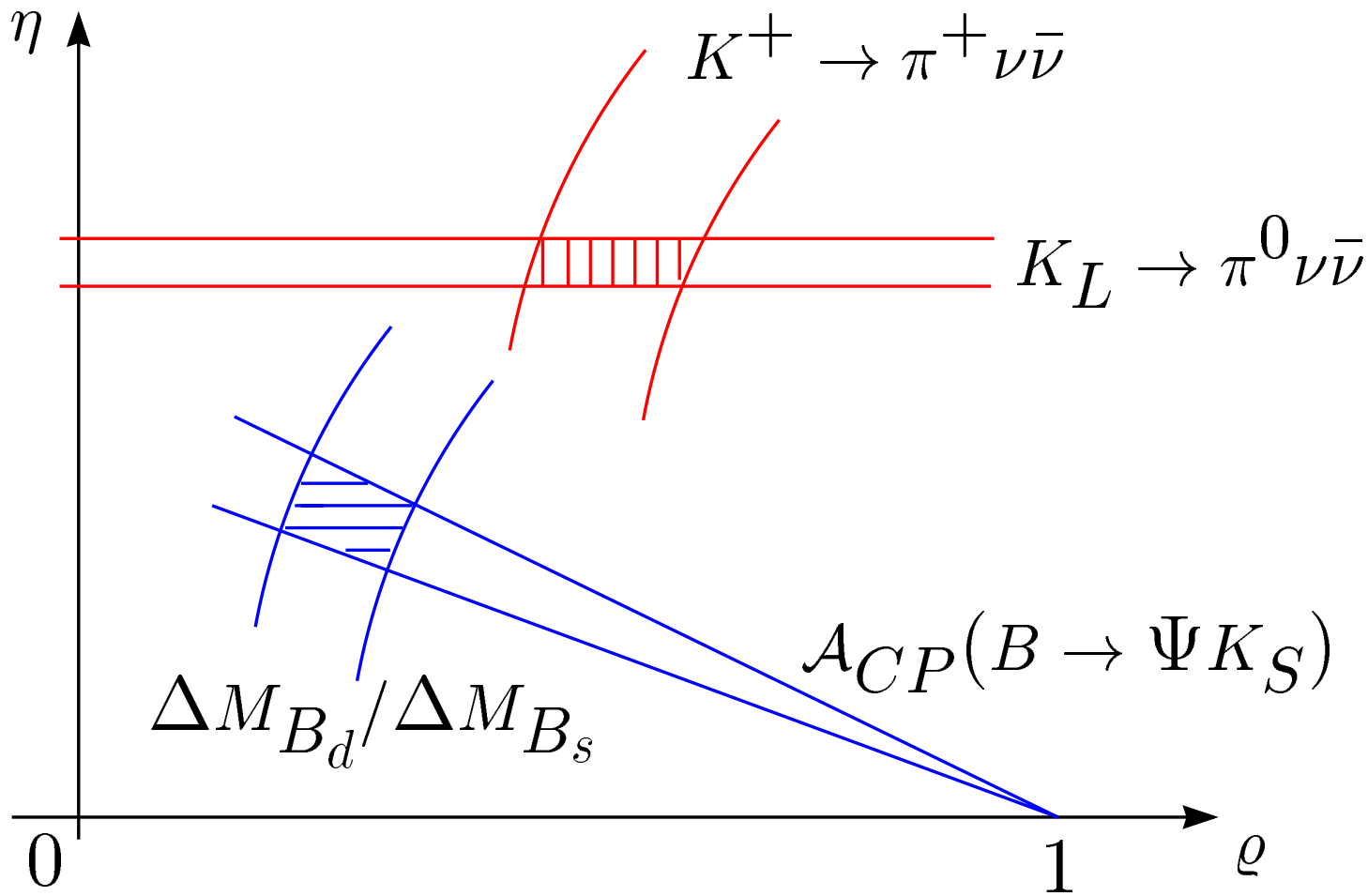
Critical measurements and tests of the Standard Model:

- Determine $Im(\lambda_t)$ and J_{CP} to 7–8% (now 22% and ~40%) with $K_L^\circ \to \pi^\circ\nu\bar{\nu}$.
- **Overconstrain β from $B_d^\circ \to \psi K_S^\circ$ and $K_L^\circ \to \pi^\circ\nu\bar{\nu}$ / $K^+ \to \pi^+\nu\bar{\nu}$**
- **Overconstrain $|V_{td}|$ from $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+\nu\bar{\nu}$**

Thanks to my E949 colleagues for their help in preparing this presentation. Particularly to David Jaffe and Joe Mildenberger for most of the slides.

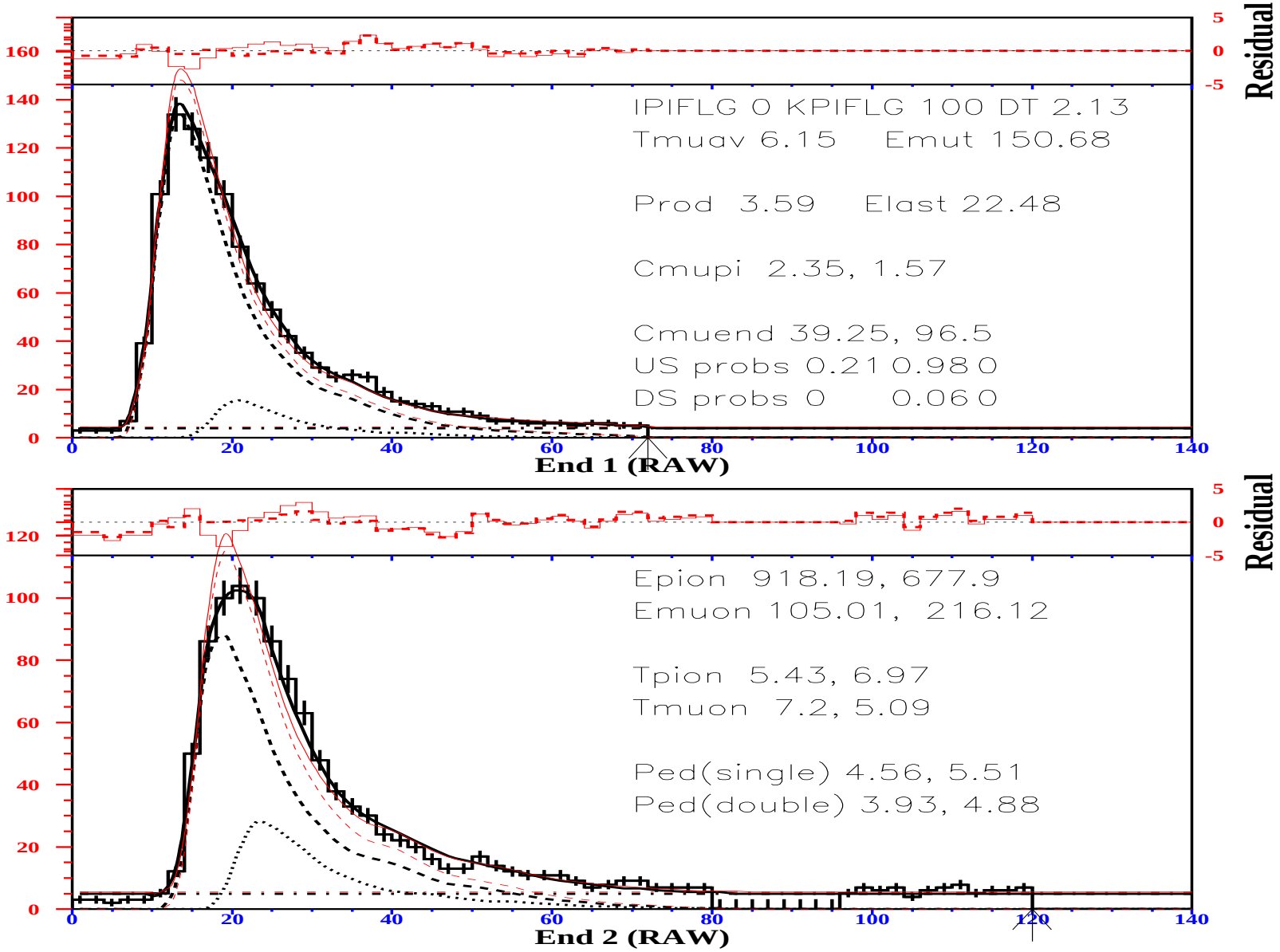
Thanks also to Gino Isidori for the figure showing the current $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ on the Unitarity Triangle.

Possible Future

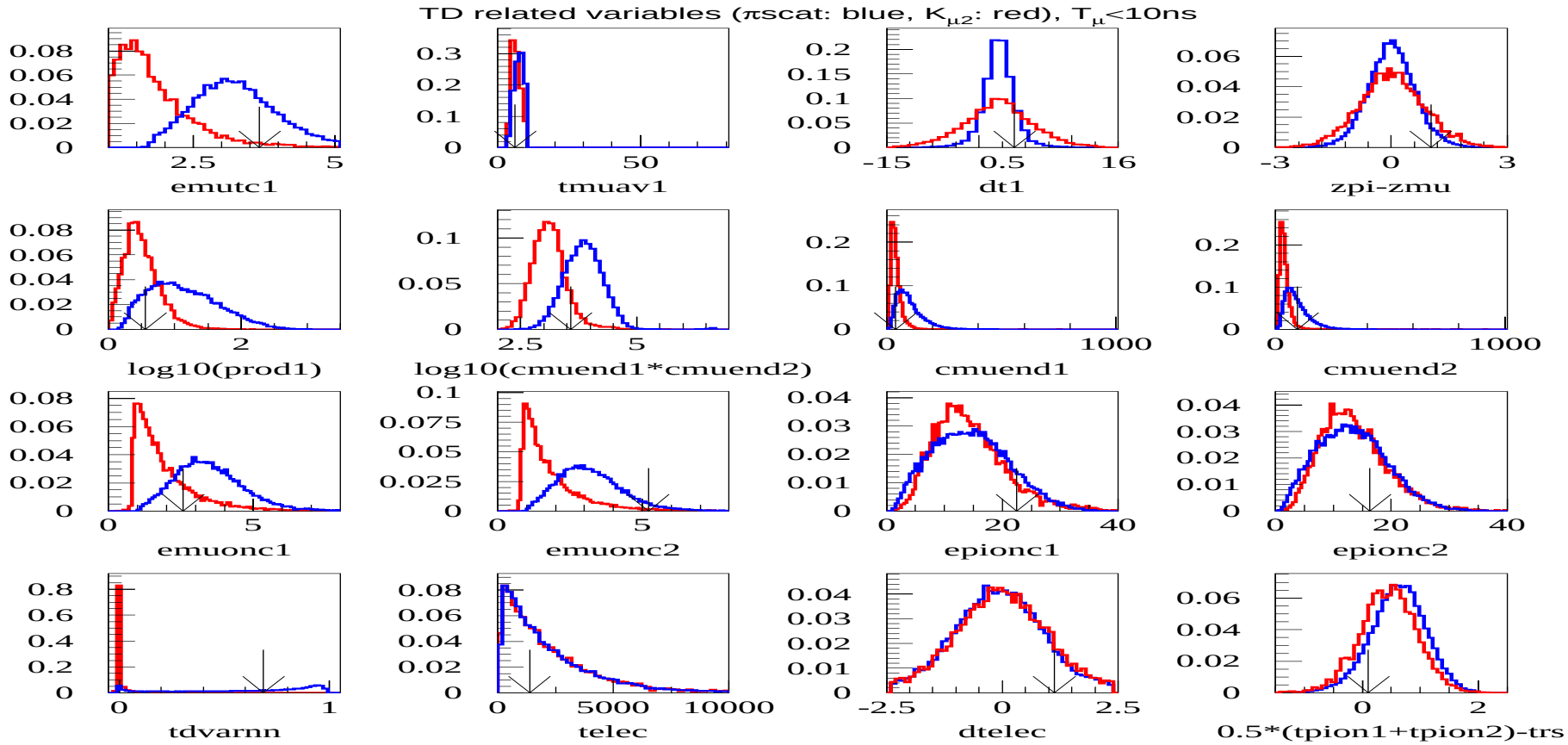


Extras

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 early fitted muon times < 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.

Opening the box

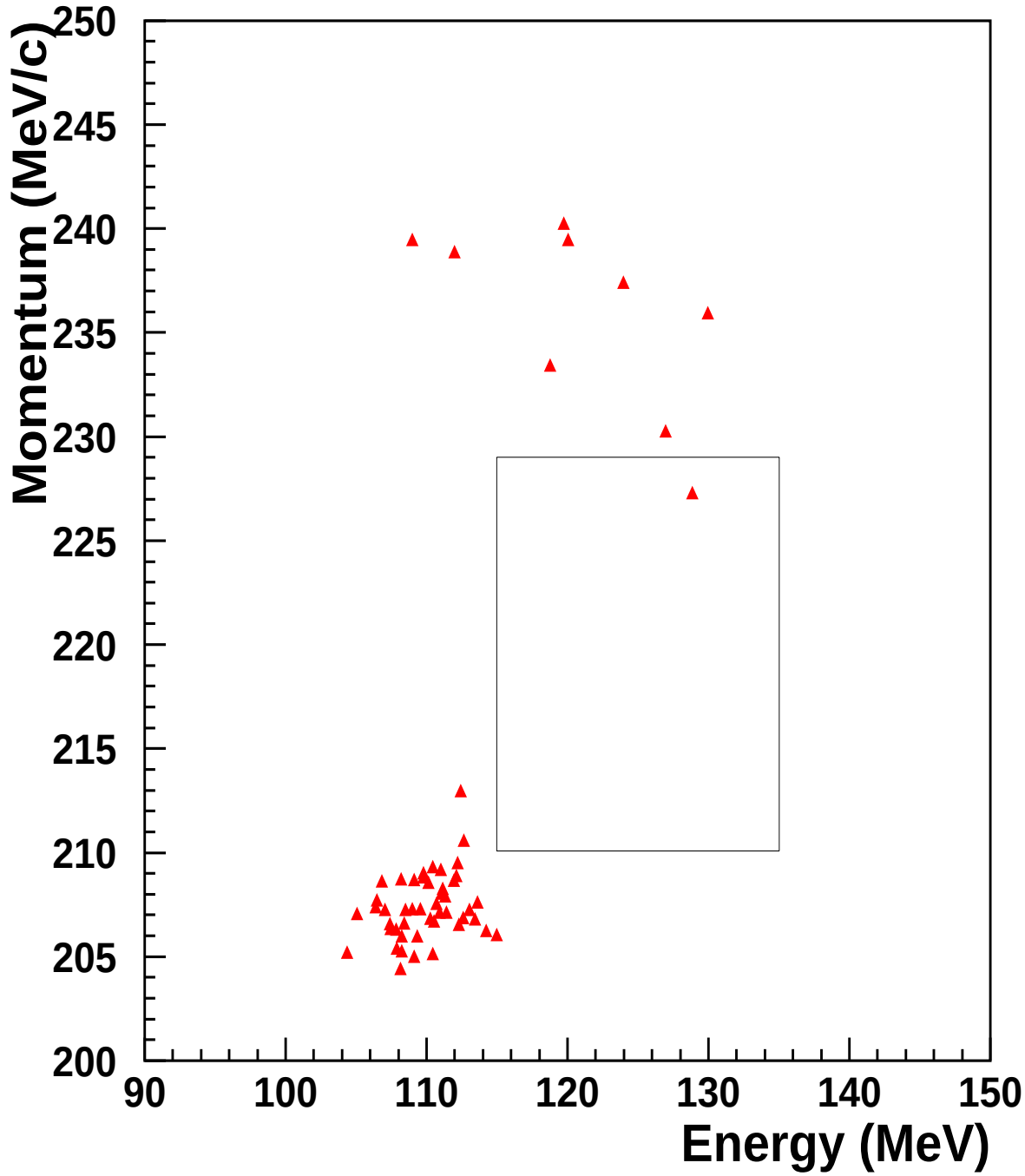
Same candidate, different variables.

Momentum (MeV/c) *vs* Energy (MeV/c) for E949 data after all other cuts applied.

Solid line shows signal region.

Events above signal region are unvetoed $K^+ \rightarrow \mu^+ X$

Cluster near 110 MeV is unvetoed $K^+ \rightarrow \pi^+ \pi^0$.



Method by T. Junk [NIM A434, 435 (1999)]

- Use background functions to subdivide signal region into many small "cells", keeping track of differential acceptance and background in each one
- Define an optimal "test statistic" X, the likelihood ratio:

$$X = \prod_{i=1}^{M} X_i$$

$$X_i = \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!} / \frac{e^{-b_i} b_i^{d_i}}{d_i!} = e^{-s_i}\left(1+\frac{s_i}{b_i}\right)^{d_i}$$

b_i, s_i : expected signal, background in each bin
d_i : #observed events in each bin

- Compute the Poisson probabilities for $s+b$ and b only:

$$P_{s+b} = \prod_{i=1}^{M} P_{s+b}(d_i; s_i+b_i) = \prod_{i=1}^{M} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!}$$

$$P_b = \prod_{i=1}^{M} P_b(d_i; b_i) = \prod_{i=1}^{M} \frac{e^{-b_i} b_i^{d_i}}{d_i!}$$

Method by T. Junk (continued)

• Get the conf. lim. by finding (and summing) all sets of d_i that give $X \leq X_{obs}$ for $s+b$, and b only:

$$\begin{aligned} CL_{s+b} &= P_{s+b}(X \leq X_{obs}) \\ &= \sum_{X(\{d'_i\}) \leq X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d'_i}}{d'_i!} \\ CL_b &= P_b(X \leq X_{obs}) \\ &= \sum_{X(\{d'_i\}) \leq X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(b_i)}(b_i)^{d'_i}}{d'_i!} \end{aligned}$$

• Finally, get the (upper limit) BR($K^+ \to \pi^+ \nu\bar{\nu}$) from the "Modified Frequentist" confidence level:

$$CL_s = CL_{s+b}/CL_b$$

• Scan over large range of "expected signal" to get a complete set of confidence levels.

$K^+ \to \pi^+ \nu\bar{\nu}$ and background rates

Process	Rate
$K^+ \to \pi^+ \nu\bar{\nu}$	0.77×10^{-10}
$K^+ \to \pi^+ \pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \to \mu^+ \nu$	$6343000000.00 \times 10^{-10}$
$K^+ \to \mu^+ \nu\gamma$	$55000000.00 \times 10^{-10}$
$K^+ \to \pi^0 \mu^+ \nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.00 \times 10^{-10}$

CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+ \ell^- \nu)$; ℓ^- is μ^- or e^-

$K^+ n \to K^0 X$ rate is empirically determined.

Summary

2002 background

Background	Events
$K_{\pi 2}$	0.216 ± 0.023
$K_{\mu 2}$	0.044 ± 0.005
$K_{\mu m}$	0.024 ± 0.010
1-beam	0.006 ± 0.002
2-beam	0.003 ± 0.002
CEX	0.005 ± 0.001
Total	0.298 ± 0.026

2002 Sensitivity

	E787	E949
# K^+	5.9×10^{12}	1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002	0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}	2.6×10^{-10}
Total Background	0.14 ± 0.05	0.30 ± 0.03

some of our cuts

Trigger

- $KB \times T.2 \times (6_{ct} + 7_{ct})$
- Delco
- 19_{ct}, L0rr, L0zfrf
- PV: $HEX \times BV \times BVL \times EC$
- L1.n

Pass0

- TRBIT
- LEV12
- RD_TRK
- STLAY
- BAD_STC
- RSHEX
- TRKTIM
- FITPI
- UTC, UTC1
- RDUTM
- PDC
- LAY14
- RANGE1
- RSHEX2

TD

- TDTCON
- EV5
- ELVETO
- TDFOOL
- TDVAR*

PV

- BV
- BL
- EC
- RD
- TG
- IC
- VC
- CO
- CM
- EC1
- BV SAST
- RD SAST
- RD SABT
- RD NABT
- RD BAST
- BV SABT
- BV NABT
- BV BAST
- EC2
- BL BAST

Beam

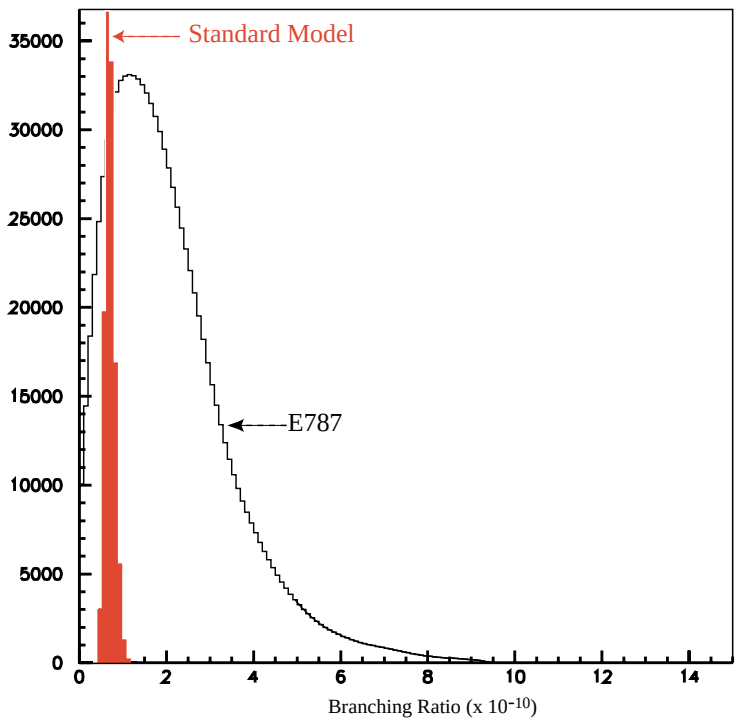
- B4DEDX
- B4CCD
- B4TRS
- BWTRS
- CKTRS, CKTAIL
- CPITRS, CPITAIL
- DELC
- B4EKZ
- B4ETCON
- DRP
- DTGTTP
- EPIMAXK
- EPITG
- EIC, KIC, TIC
- OPSVETO
- OPSVETO_LKB
- PHIVTX, PHIVTX2
- RTDIF
- TARGF
- TGEDGE
- TGER
- TGGEO
- TGQUALT
- TIMCON
- TGZFOOL
- TGTCON
- UPV/RVTRS
- • •

Kinematic

- LAYV4
- LAYER14
- COS3D
- ZFRF
- ZUTOUT
- UTQUAL
- CHIMAX
- CL_RSDEDX
- RS_LIKE
- PR_RF
- PR_RF_XY
- PR_RFZ1
- PR_RFZ2
- TGDEDX
- LIKE
- LIKE2
- DB4
- DB4TIP
- DVXTIP
- PIGAP
- RNGMOM
- • •

E787: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

Event	Kinematic quantities $P(MeV/c)$	$R(cm)$	$E(MeV)$	SM S/N	Bkg	Rel. acc
1995	218.2	34.8	117.8	35	0.008	0.55
1998	213.8	33.9	117.1	3.6	0.022	0.84
B2(98)	224.9	37.1	125.5	0.7	0.11	1.24



E787 Summary

- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$
  (SM: $0.75 \pm 0.29 \times 10^{-10}$)

84% CL lim. (68% CL int.)	90% CL lim. (80% CL int.)	95% CL lim. (90% CL int.)	99% CL lim. (98% CL int.)
[0.749,3.323]	[0.560,3.886]	[0.366,4.694]	[0.132,6.452]

- $P_b \sim 0.1\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% CL)
- already has non-trivial impact on CKM fits [PL **B530**, 108 (2002)]