E949 experiment (BNL)
(measuring $K^+ \to \pi^+ \nu \bar{\nu}$ decay)
Status and new results

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IHEP Seminar

April, 8 2004

The E949 Collaboration

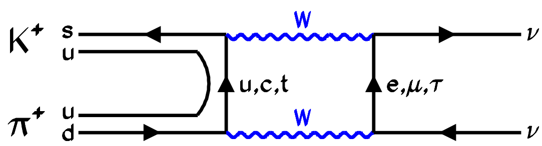
- U.S.
  BNL, FNAL, New Mexico
- Canada
  TRIUMF, UBC, Alberta
- Japan
  Fukui, KEK, Kyoto, Osaka
- Russia
  IHEP, INR

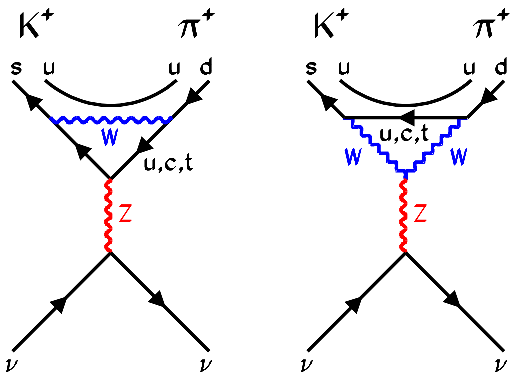
Outline

- $K^+ \to \pi^+ \nu \bar{\nu}$
- E949
  - Detector
  - 2002 Run summary
  - E949 Analysis
- Results
- Status and the future

$K^+ \to \pi^+ \nu \bar{\nu}$ in the Standard Model

3-generation Standard Model:
F.C.N.C. highly suppressed by GIM mechanism





- The main contribution is made by the region $r \sim 1/m_t,\ 1/m_Z$, hence accurately acounted in the framework of perturbative QCD.

- The hadron matrix element $\langle \pi | H_w | K \rangle_{\pi \nu \bar{\nu}}$ can be related to $\langle \pi | H_w | K \rangle_{\pi e \nu}$ of the well measured decay $K^+ \to \pi^0 e^+ \nu_e$.

- Total theoretical uncertainty $\sim 5\%$

- Current SM prediction: $(0.77 \pm 0.11) \times 10^{-10}$

Connection to $|V_{td}|$

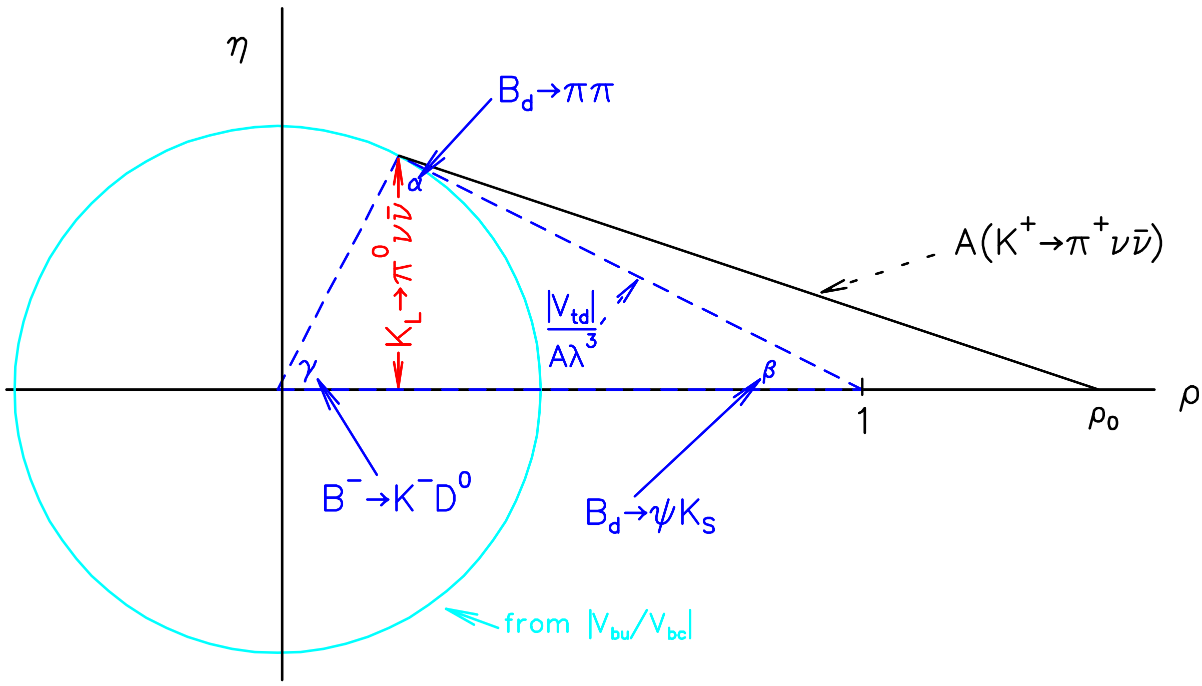
- $B(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}) \propto |V^*_{cs} V_{cd} F(x_c) + V^*_{ts} V_{td} F(x_t)|^2$, $x_{c,t} = (m_{c,t}/m_W)^2$, $F(x_c)/F(x_t) < 10^{-3}$

Connection to Unitarity Triangle

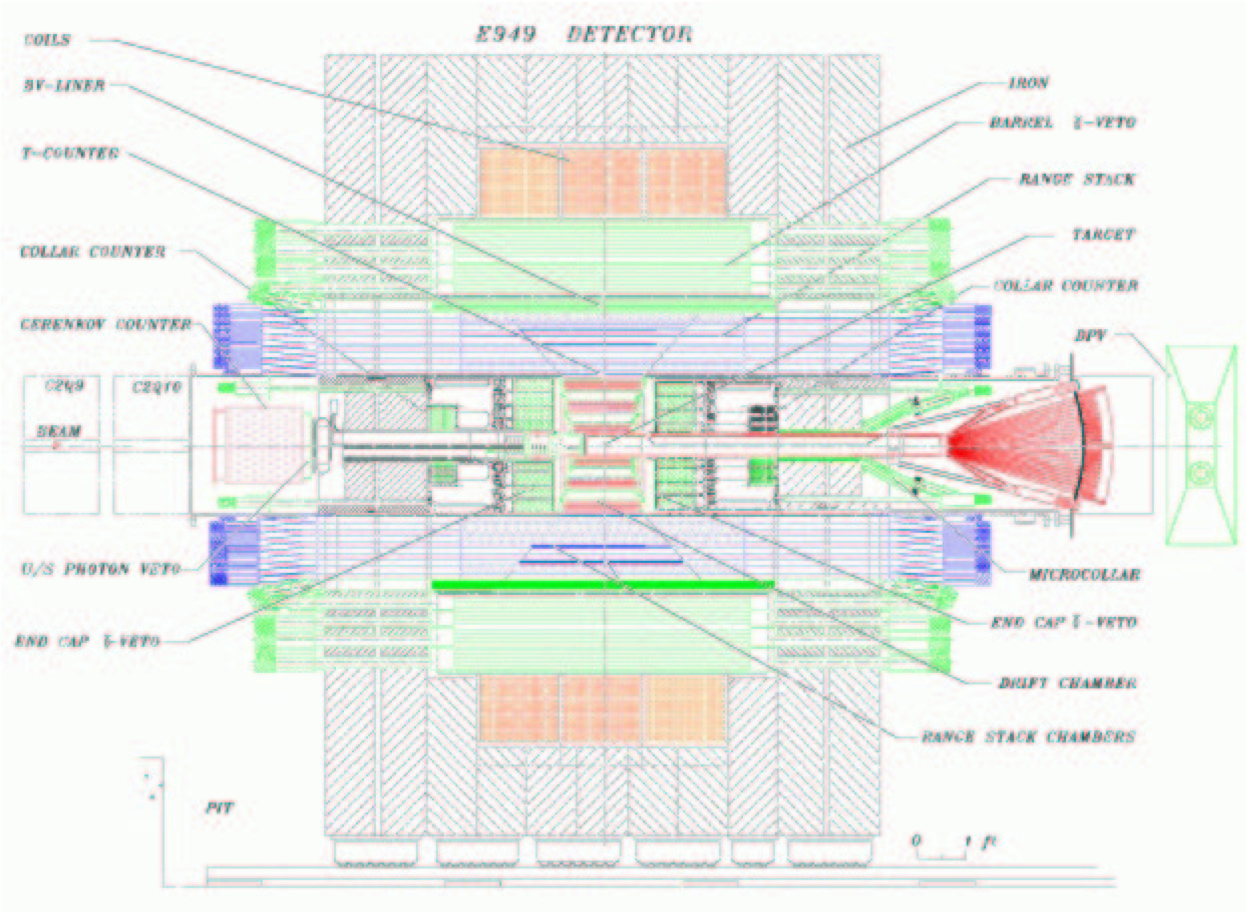
$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Wolfenstein parametrization: $\lambda \equiv \sin\theta_c = V_{us}$

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



E949 Detector



Elevation view of the E949 detector.

Detection Strategy

Stopped K^+

- two-body decay backgound has fix energy of its decay products
- easy to suppress K in flight decay and other beam time background

Redundancy

- redundant measurements (P, E, R is measured for π^+)
- minimum dead matherial, all detector elements are active (degrader, target)
- detail information is recorded (Q, T, pulse shape)

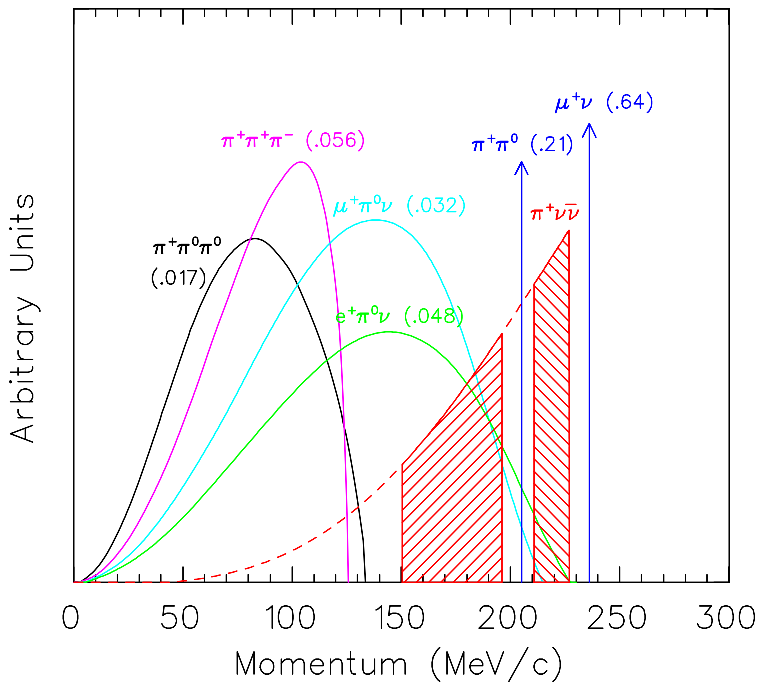
Positive i.d. of beam and decay particle

- Čerenkov for beam K^+, observing $\pi \to \mu \to e$ decay chain for π^+

Strong 4π-srad chanrge and gamma veto energy ($\sim 17X$ in perpendicular direction)

Clean K^+ beam ($K/\pi = 4/1$)

Backgrounds

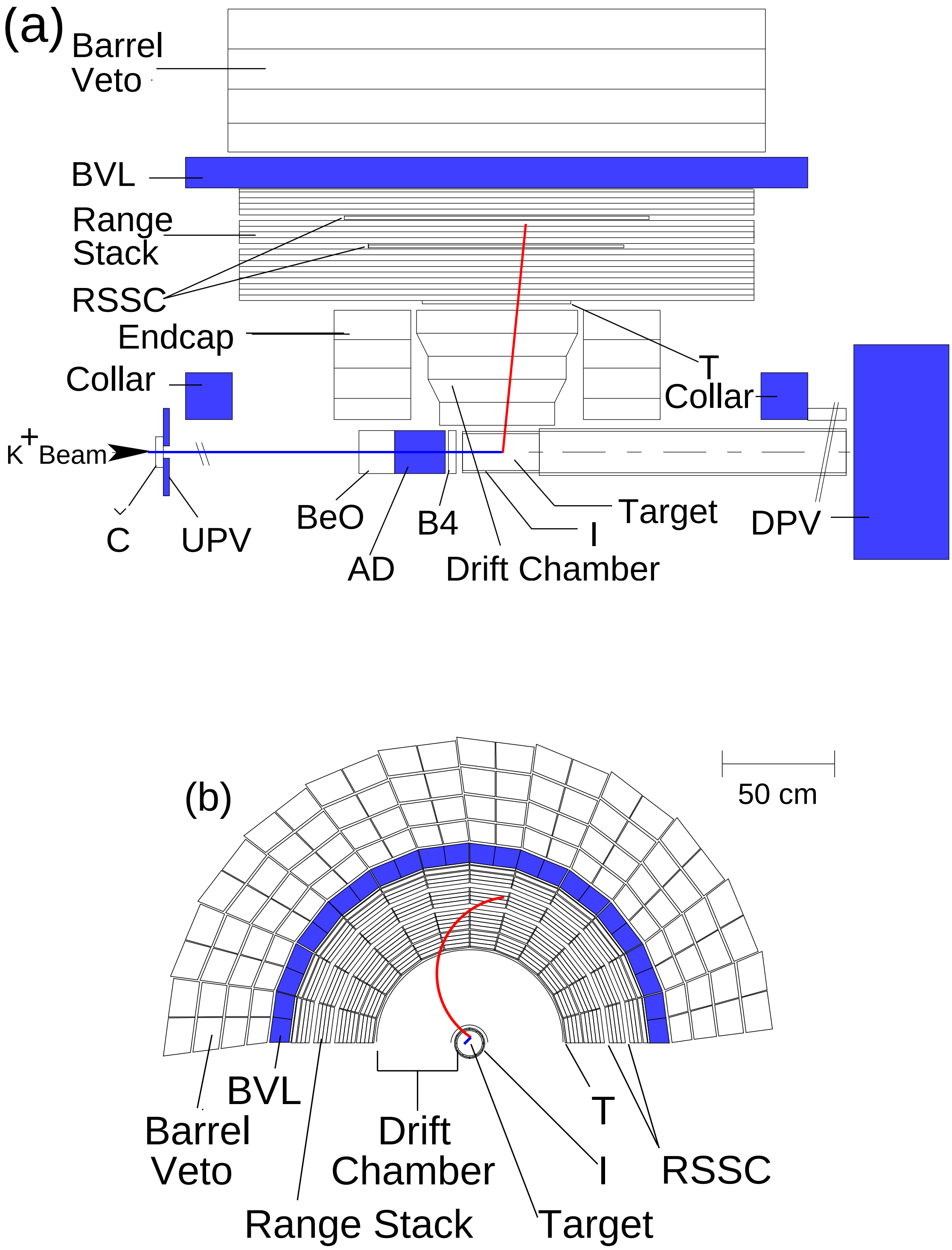


Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.77×10^{-10}
$K^+ \to \pi^+\pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu$	$6343000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$55000000.00 \times 10^{-10}$
$K^+ \to \pi^0\mu^+\nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$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

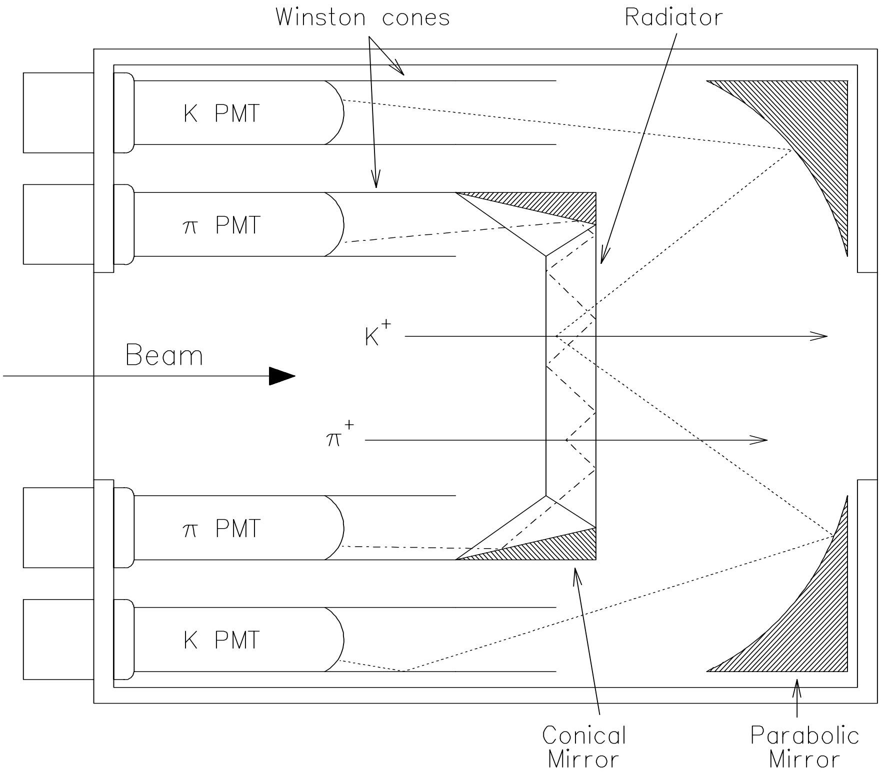
CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\ell^-\nu)$

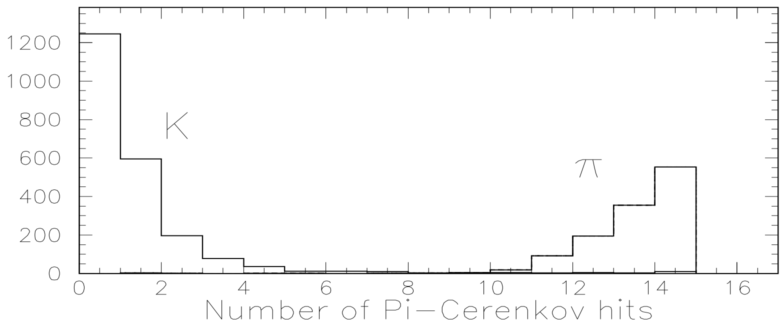
$K^+ n \to K^0 X$ rate is empirically determined.

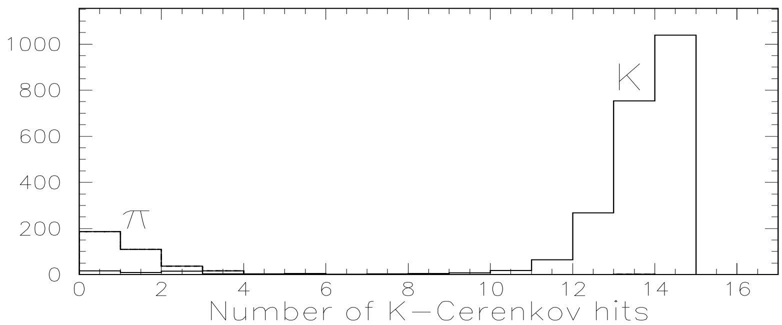
E949 Detector



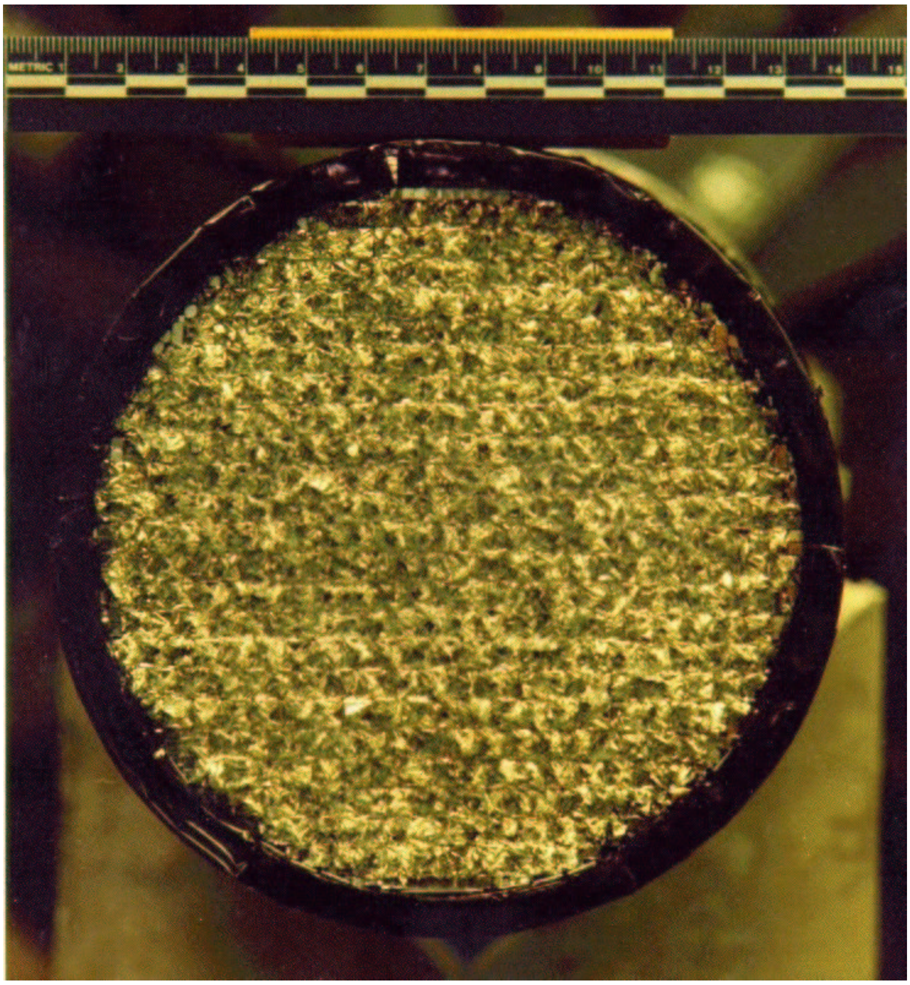
Beam Čerencov



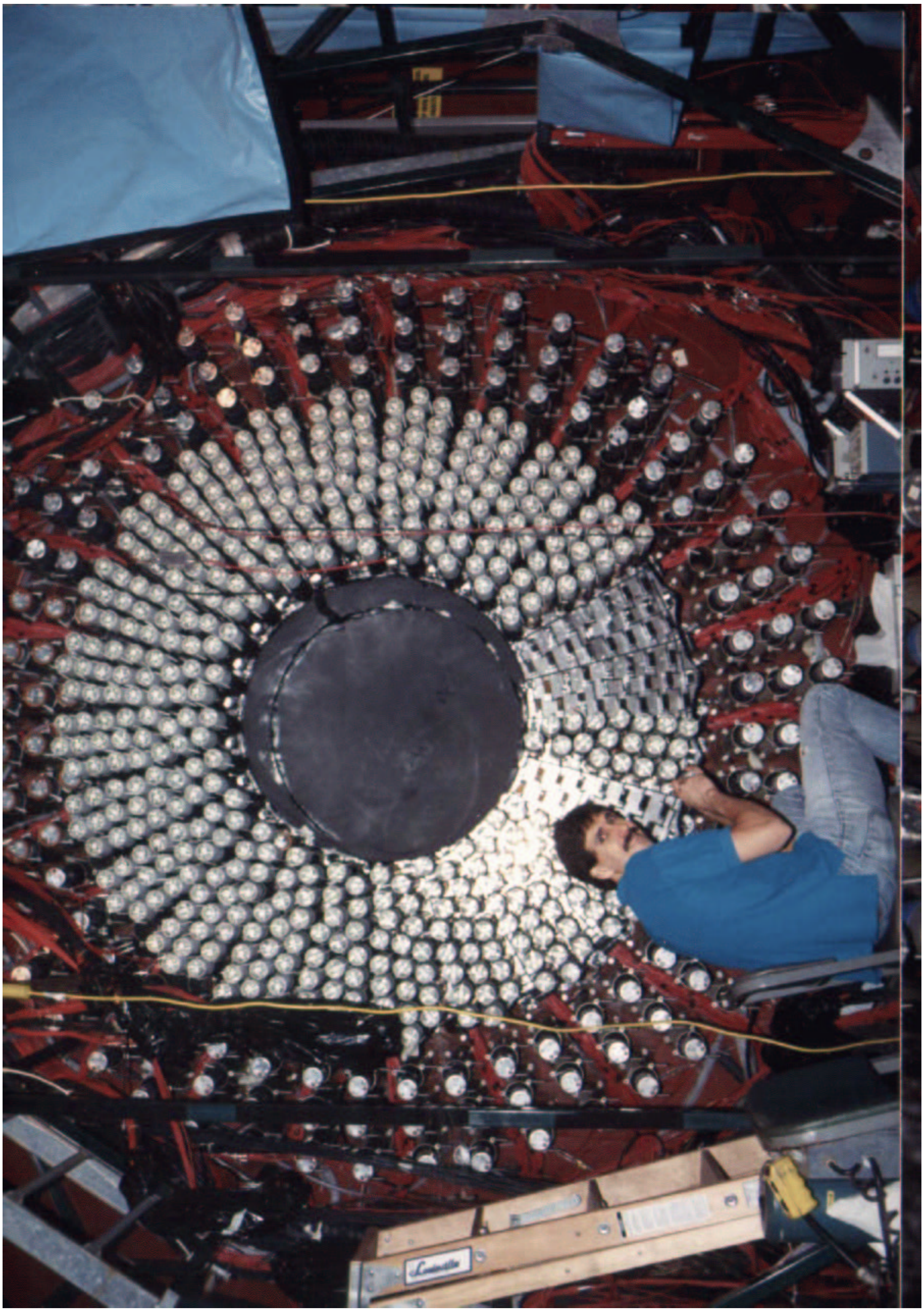




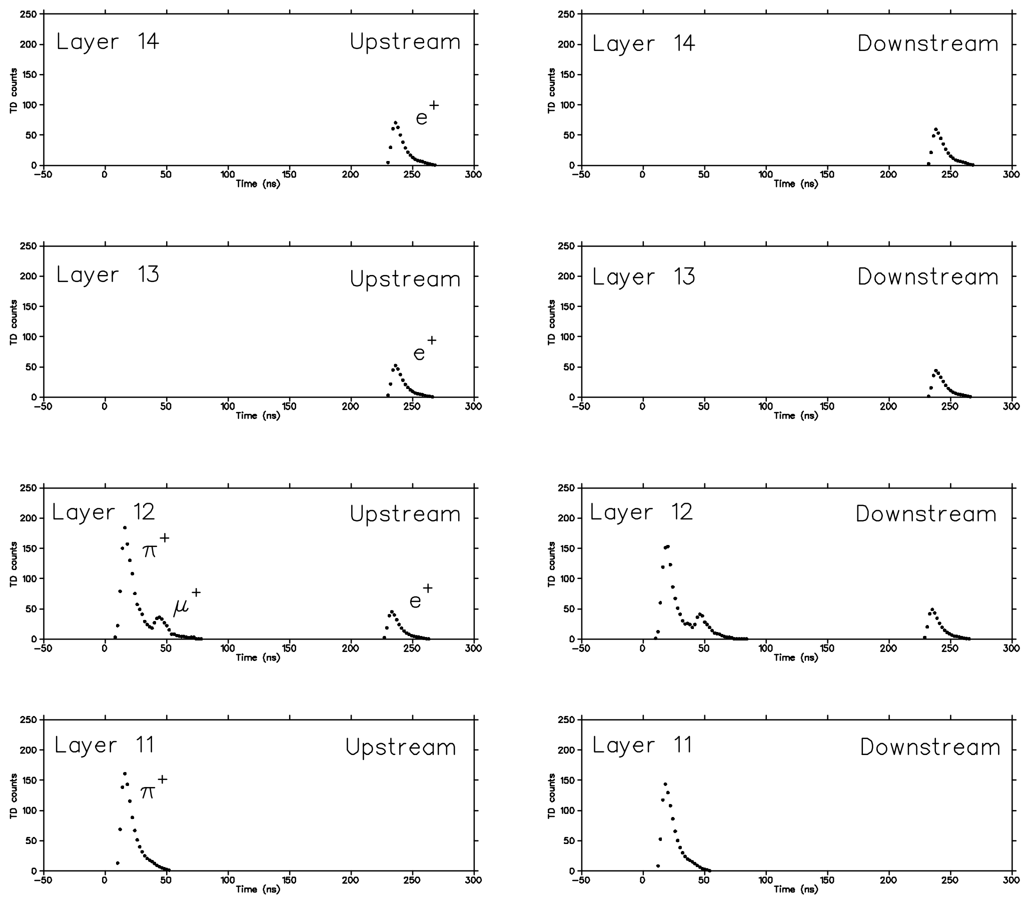
Target



Range Stack



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



- $\pi^+ \to \mu^+\nu$: $\tau_\pi = 26$ ns, $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm
- $\mu^+ \to e^+\nu\bar{\nu}$: $\tau_\mu = 2.2\,\mu$s, $E_e \leq 53$ MeV

Some history

E787

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

E949

Upgrades:

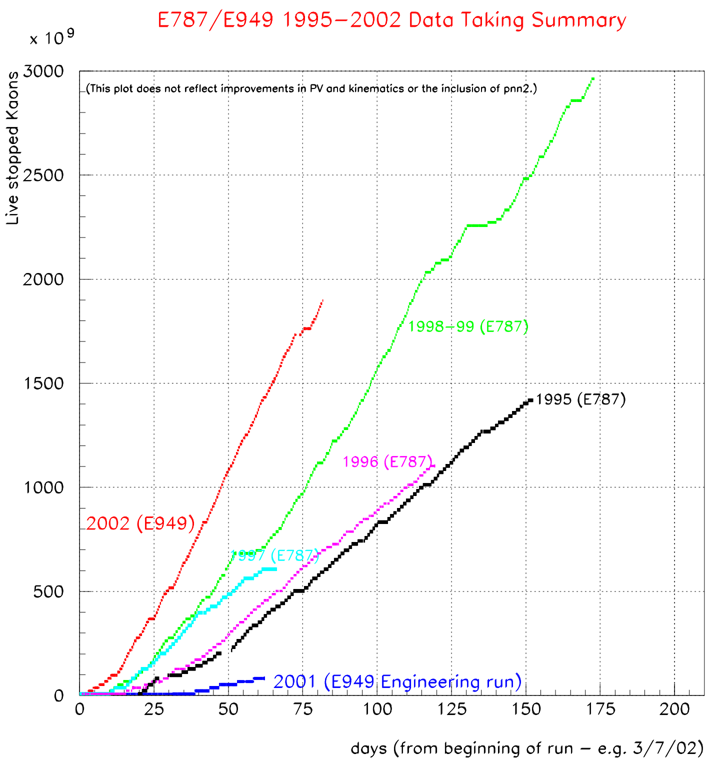
- More protons/sec from AGS
- Higher rate capability due to DAQ and trigger improvements
- Improved photon veto hermeticity
- Improved tracking and energy resolution

Goals:

- 60 weeks of running FY01-03
- 5-10 SM events

Reality

- 12 weeks of running FY02
- Not optimal in 2002:
  - Spill duty factor (2.2/5.4s vs. 4.1/6.4s, 2.5 vs. 5M live stopped K/spill
  - Proton beam momentum (22 GeV vs. 24 GeV)
  - Lower K/π ration (3/1 vs 4/1)



Analysis Goals

E787

- Define a "signal box", don't look in it until the very end ("Blind" analysis)
- Construct cuts to have the level of background < 0.1 event in the signal box
- Open the signal box, count events

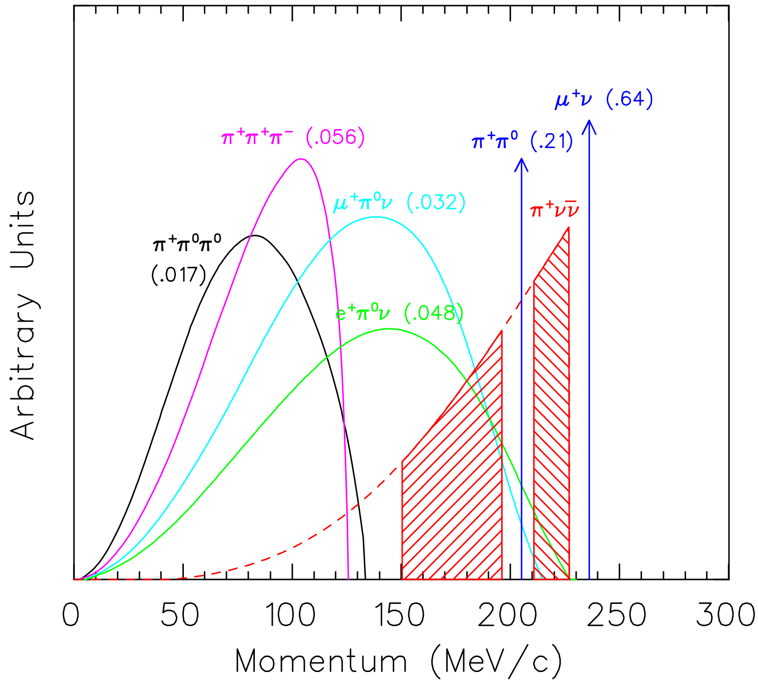
E949

- Choose a "signal box", don't look in it until the very end ("Blind" analysis)
- Construct cuts to have the level of background < 0.3 event in the signal box
- Open the signal box, use likelihood ratio method taking into account signal-like/background-like characteristics of events to calculate the branching ratio

Analysis Strategy

- "Blind" analysis. Don't examine signal region until all backgrounds verified.
- 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 $\mathrm{K}^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \pi^0)$.

Backgrounds



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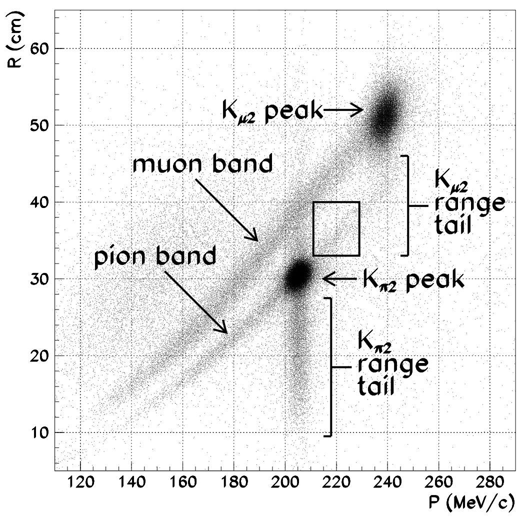
Background suppression

Source	Suppression method			
	Kin.	Part. ID	Veto	Timing
$K^+ \to \mu^+\nu(\gamma)$ ($K_{\mu 2}$)	$\surd$	$\surd$	($\surd$)	
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	$\surd$		$\surd$	
Scattered π^+ beam		$\surd$		$\surd$
CEX			$\surd$	$\surd$

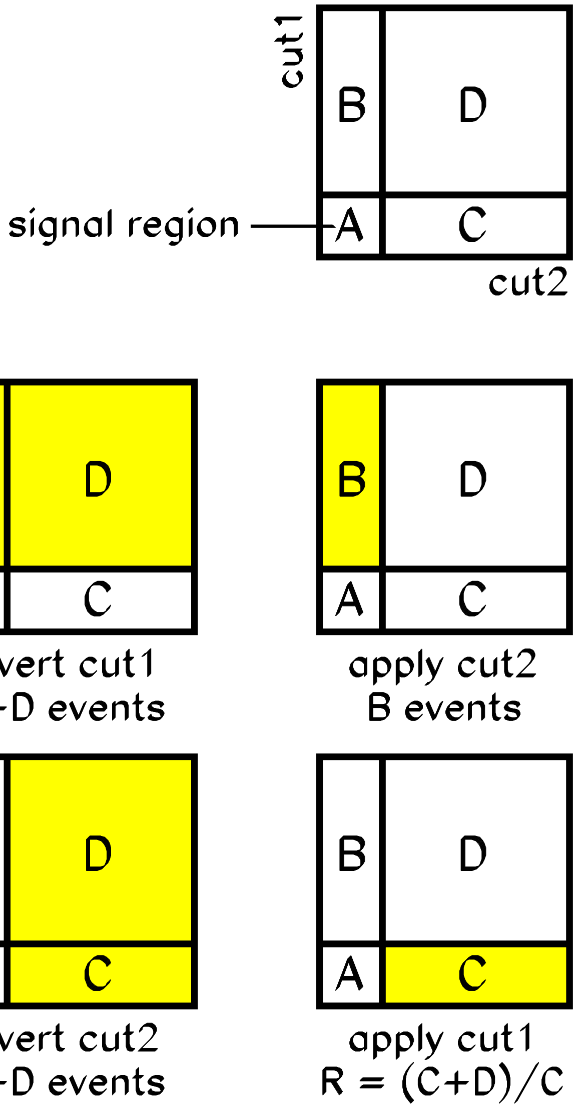
CEX $\equiv K^+ n \to K^0 p$, $K^0_L \to \pi^+ \ell^- \nu$

Particle ID includes beam Cherenkov, dE/dx and $\pi \to \mu \to e$ detection

Veto includes both photon and charged particle vetoing



Bifurcated analysis



if cut1,cut2 uncorrelated,

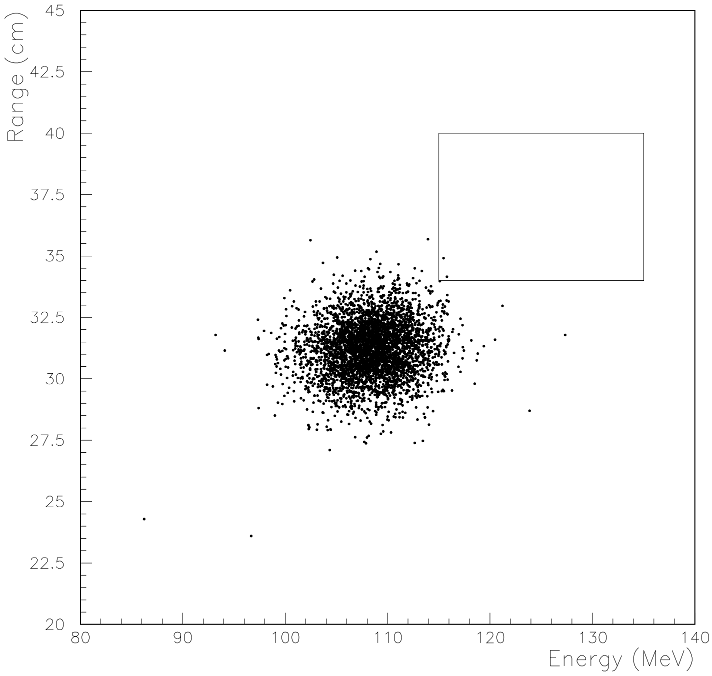
$$A/B = C/D$$

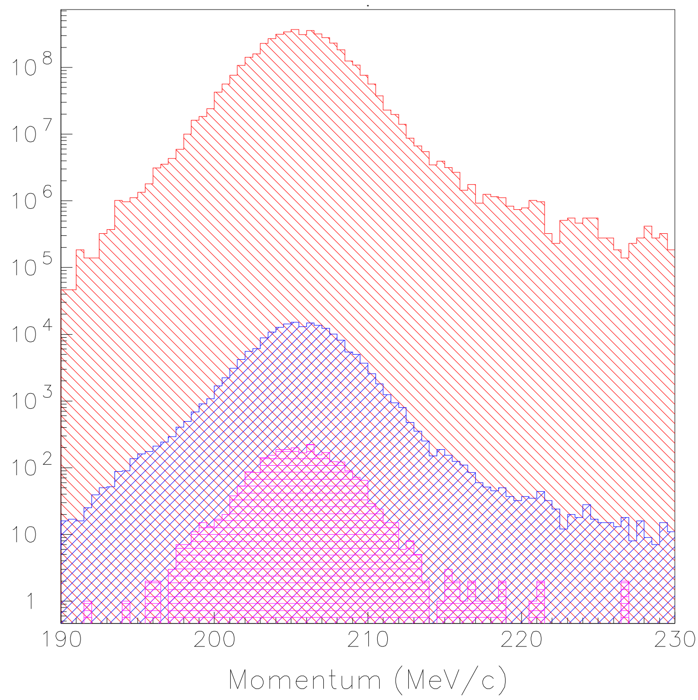
$$A = BC/D$$

$$bg = B/(R-1)$$

$$= BC/D$$

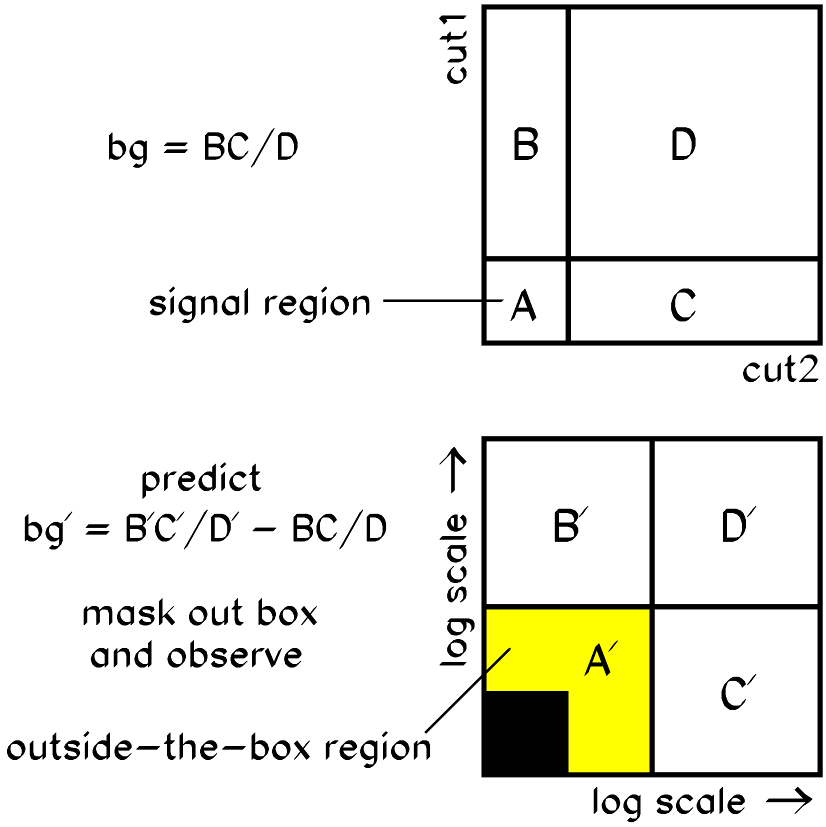
Example: $K^+ \to \pi^+\pi^0$ rejection





$$N_{b.g.} = N_{Kin.}/(R_{\bar{\gamma}} - 1)$$

“Outside box studies”



- Correlation studies
- Single-cut/double-cut failures
- Check predicted *v.* measured backgrounds
- Look for anomalies and “loop-holes” in analysis

Results

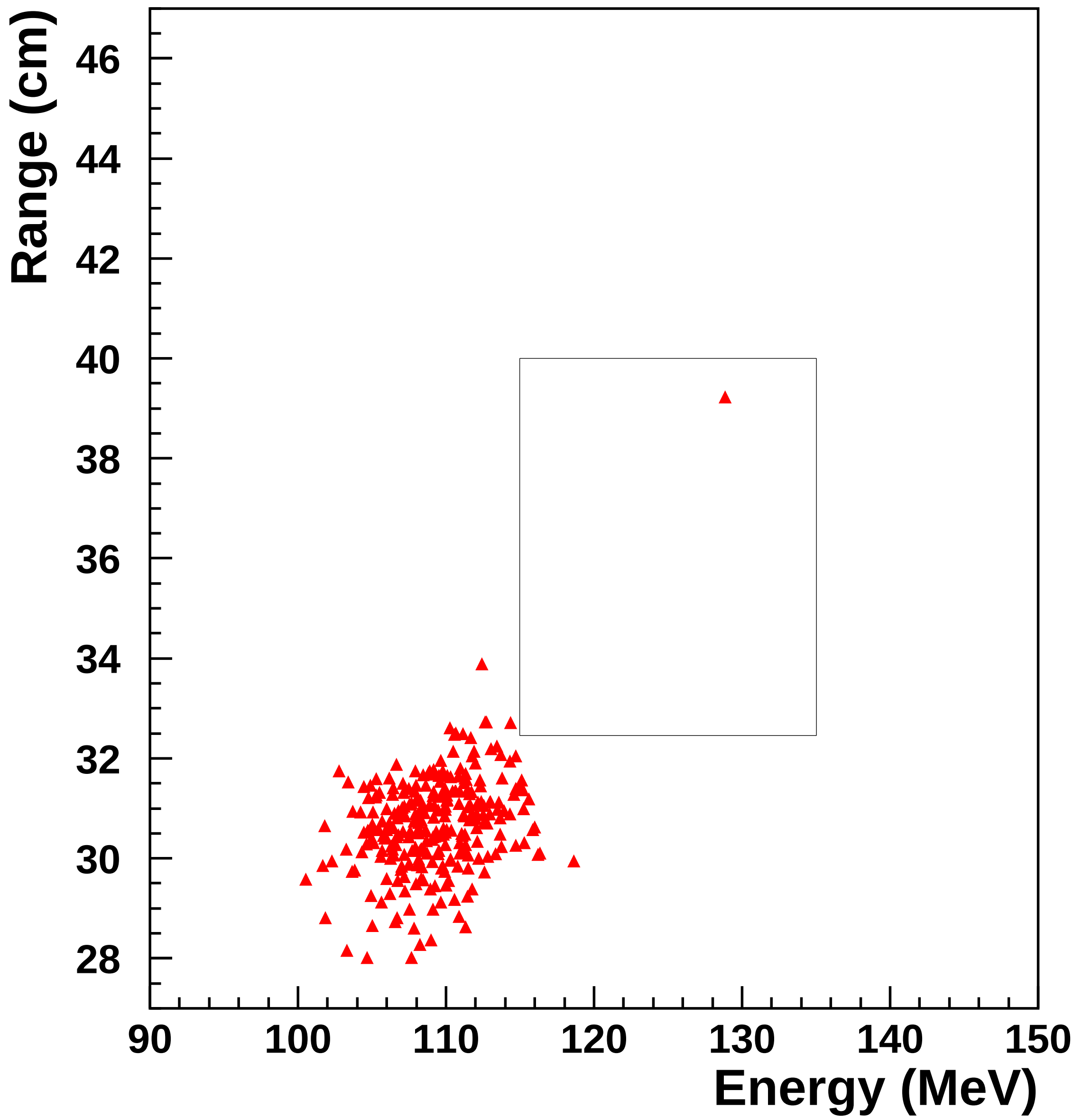
2002 background levels

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
N_K	5.9×10^{12}	1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002	0.0022 ± 0.0002
Total Background	0.14 ± 0.05	0.30 ± 0.03

Opening the box...

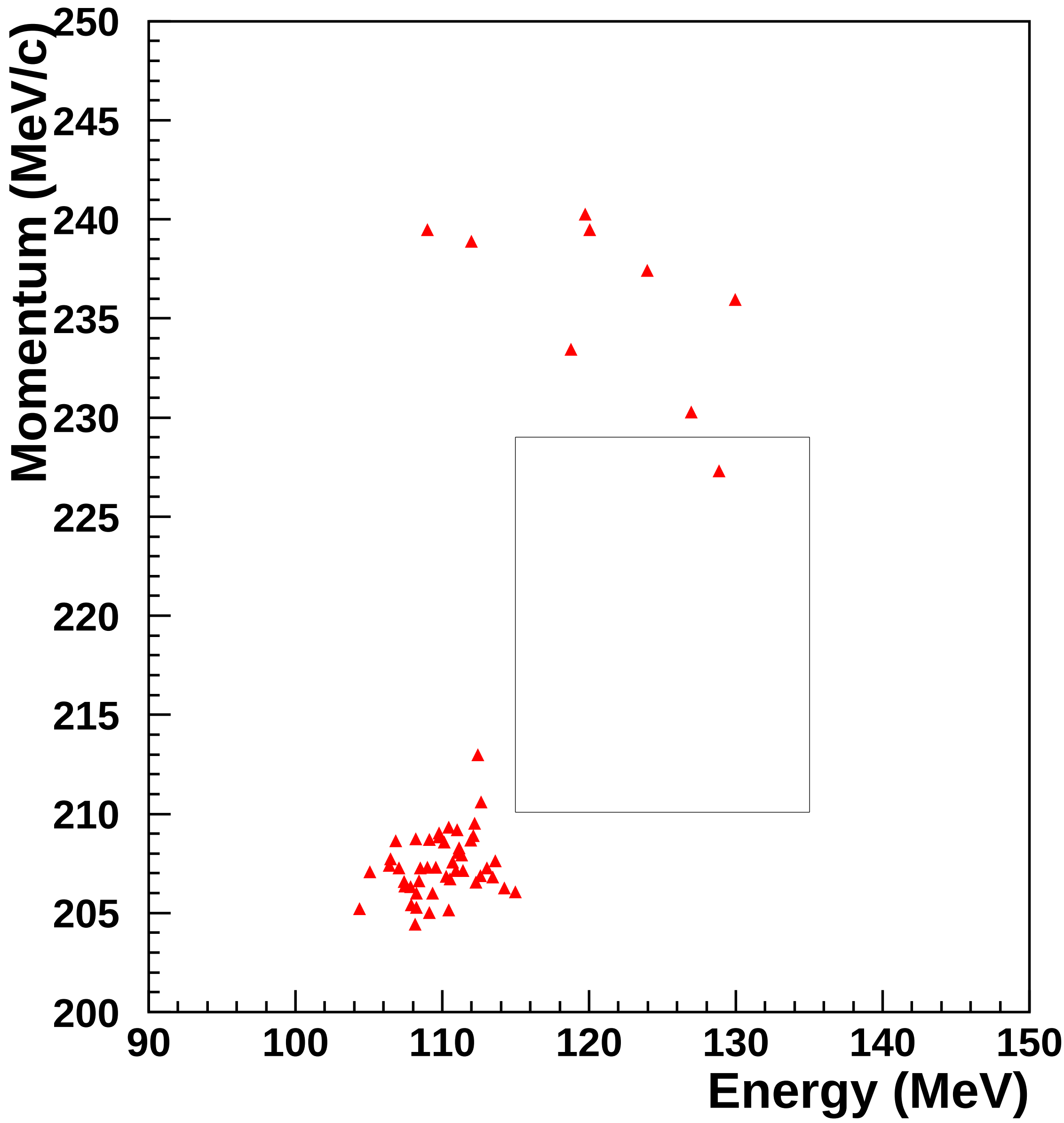


Single candidate found !

Solid line shows signal region.

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

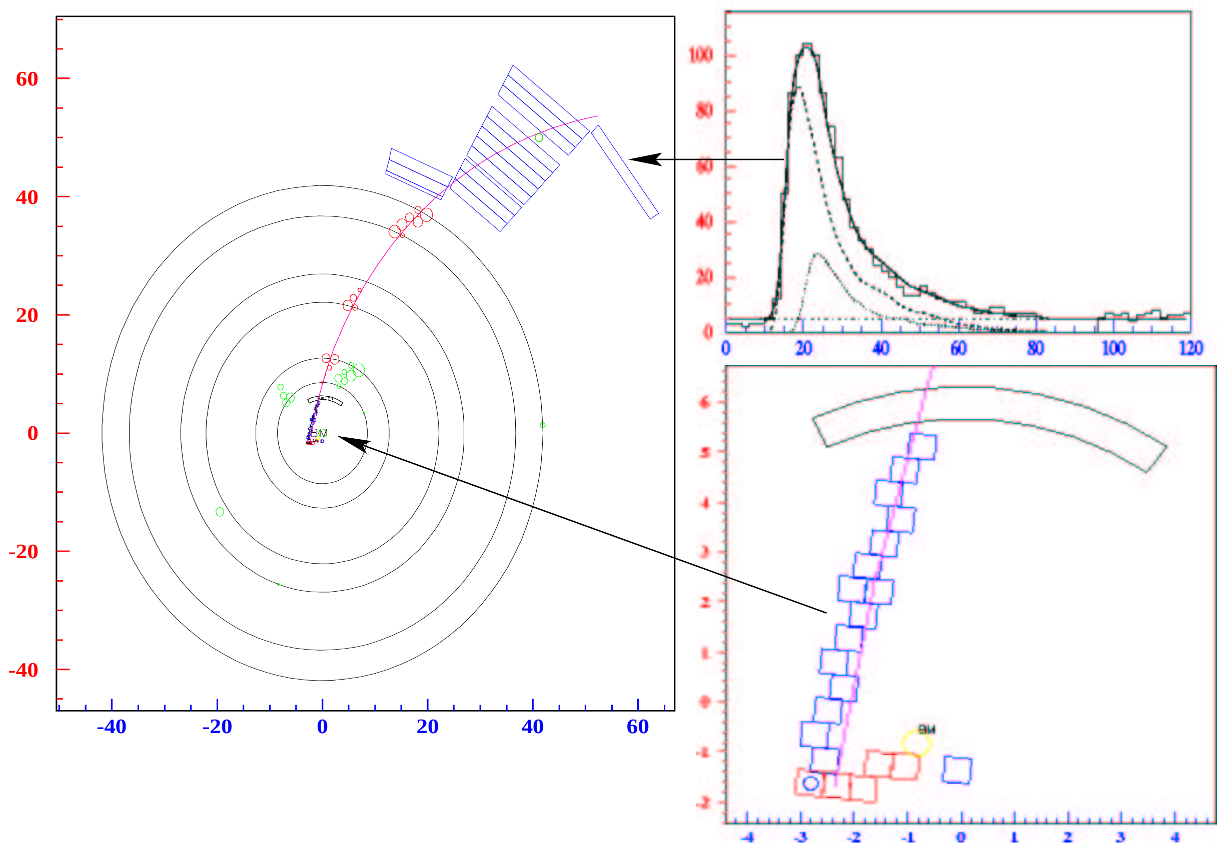
Opening the box...



Solid line shows signal region.

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

Event display



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

E787/E949 Signal Events

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

b_i = background of cell containing candidate

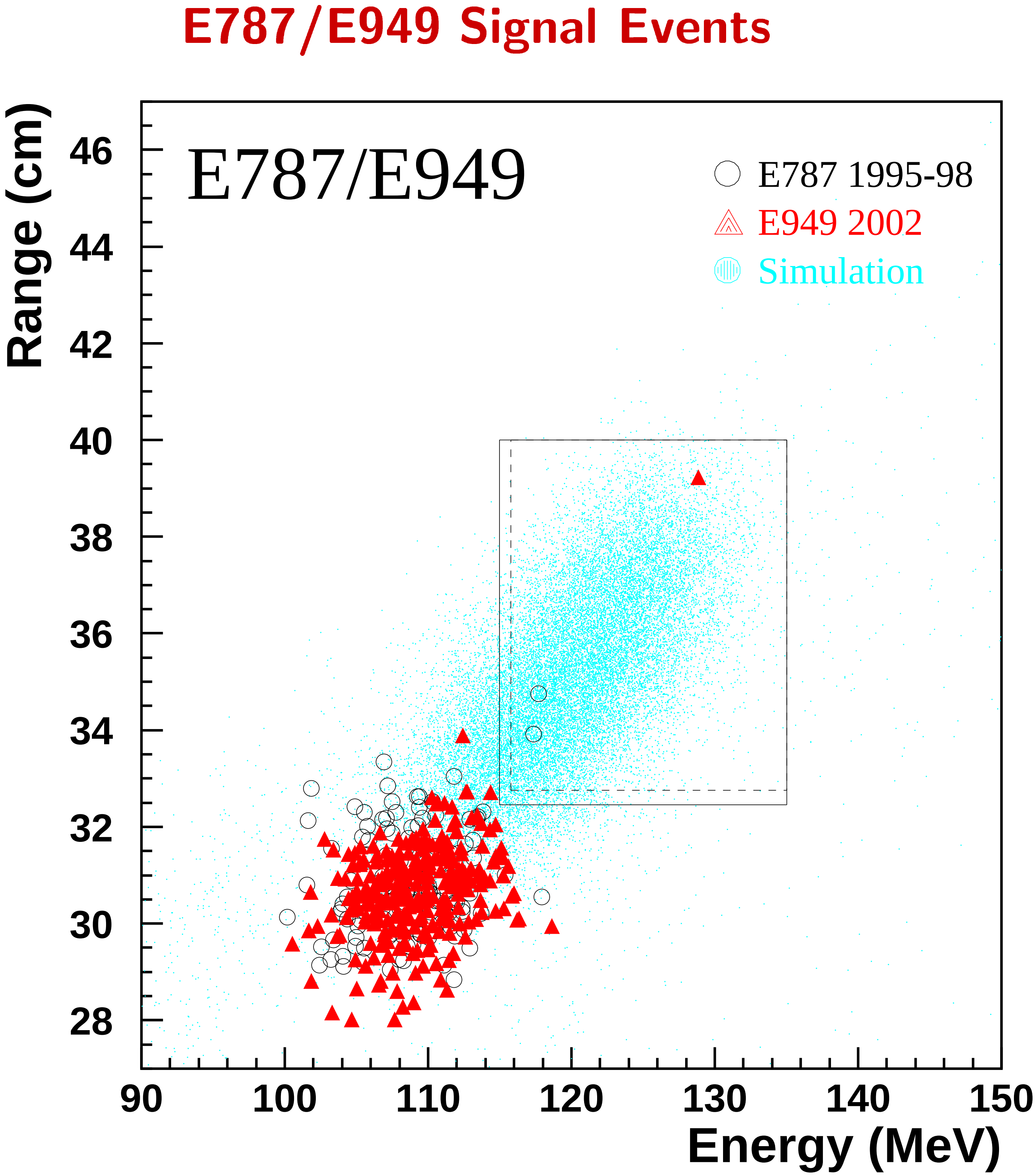
$S_i \equiv \mathcal{B} A_i N_K$ = signal for cell containing candidate

$A_i \equiv$ acceptance

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

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

Event weight W_i and S_i/b_i assumes the measured branching ratio as well as calculated background.


E787/E949 Signal Events
E787/E949
E787 1995-98
E949 2002
Simulation
Range (cm)
Energy (MeV)
28
30
32
34
36
38
40
42
44
46
90
100
110
120
130
140
150

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

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

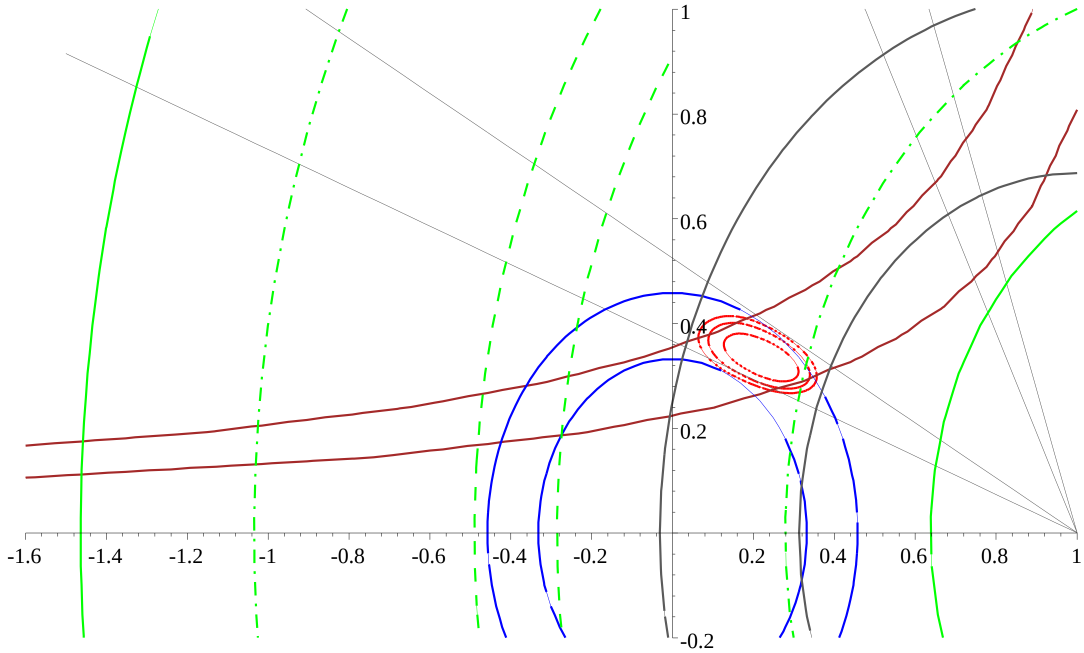
$B(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) > 0.42 \times 10^{-10}$ at 90% CL.

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

The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.

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

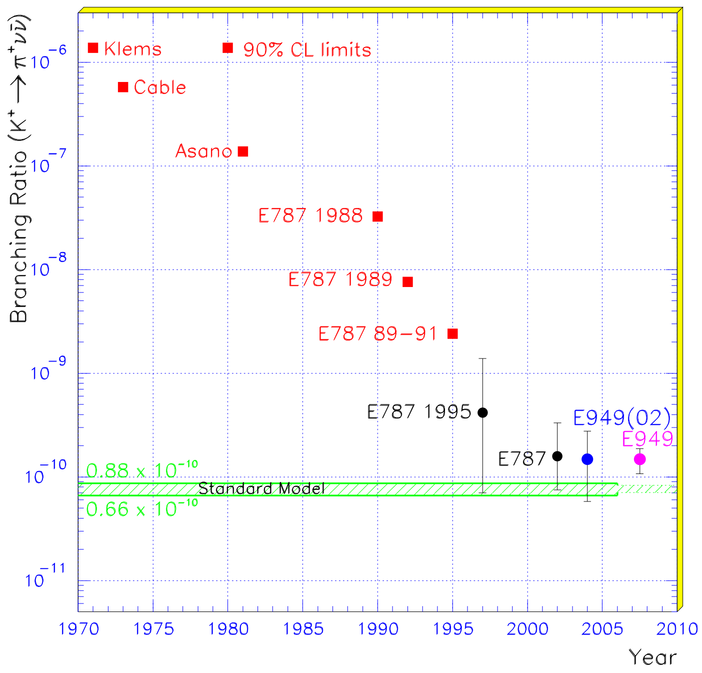
Impact of $B(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ on Unitarity Triangle

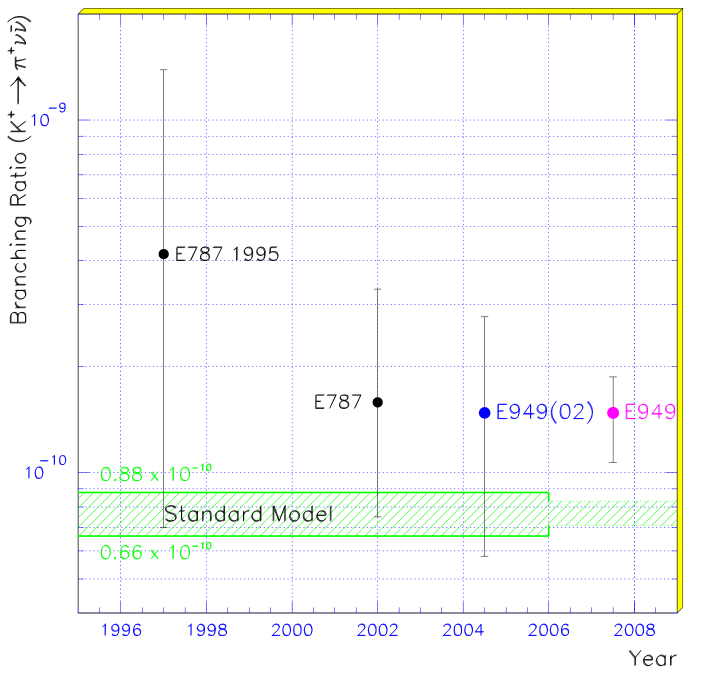


Green lines show $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ impact on Unitarity Triangle: central value (dashed), 68% interval (dot-dash), 90% interval (solid). Theoretical uncertainty is included.

Red ovals show 68%, 90% and 95% areas from other measurements ($|V_{ub}|$, ϵ_K, $\sin 2\beta$, Δm_d, $\Delta m_s/\Delta m_d$)

Progress in measuring $\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})$





E949 and the future of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$

- E949 was approved August 1999 to run for 60 weeks, concurrent with RHIC operation, over three years (U.S. FY2001 - FY2003).

- HEP operations at AGS halted for FY2003 (Feb.2002)

- E949 completes successful 12 week run (Jun.2002). AGS functioned well and E949 performed as predicted

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

- Another stopped-K^+ experiment to measure $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ under consideration at KEK in Japan. K^+ decay-in-flight experiments under consideration at FNAL and CERN.

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