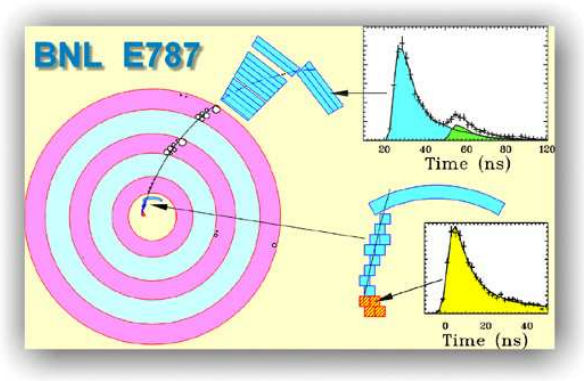

Fifth KEK Topical Conference
Frontiers in Flavor Physics
KEK
November 20–2, 2001

Kaon Physics at BNL

- $K^+ \to \pi^+ \nu\overline{\nu}$: E787/E949
- $K_L^\circ \to \pi^\circ \nu\overline{\nu}$: KOPIO

Steve Kettell
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Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN
NATIONAL LABORATORY

Recent Kaon Results from BNL

Decay Mode	Branching Ratio	Events	Experiment	Ref
	$K \to \pi\nu\bar{\nu}$			
$K^+ \to \pi^+\nu\bar{\nu}$	$(1.5^{+3.4}_{-1.2}) \times 10^{-10}$	1	E787 (2000)	**PRL 84**:3768
$K_L^\circ \to \pi^\circ\nu\bar{\nu}$ $(\pi^+\nu\bar{\nu})$	$< 2.6 \times 10^{-9}$	—	E787 (2000)	indirect
$K \to \pi^+\pi^\circ\nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	0	E787 (2001)	**PRD 63**:032004
	$K_L^\circ \to \ell^+\ell^-$			
$K_L^\circ \to \mu^+\mu^-$	$(7.24 \pm 0.17) \times 10^{-9}$	6200	E871 (2000)	**PRL 84**:1389
$K_L^\circ \to e^+e^-$	$(8.7^{+5.7}_{-4.1}) \times 10^{-12}$	4	E871 (1998)	**PRL 81**:4309
	$K^+ \to \pi^+\gamma\gamma$			
$K^+ \to \pi^+\gamma\gamma$	$(6.0 \pm 1.5 \pm .7) \times 10^{-7}$	26	E787 (1997)	**PRL 79**:4079
	$K^+ \to \pi^+\ell^+\ell^-$			
$K^+ \to \pi^+e^+e^-$	$(2.94 \pm .05 \pm .13) \times 10^{-7}$	10,300	E865 (1999)	**PRL 83**:4482
$K^+ \to \pi^+\mu^+\mu^-$	$(5.0 \pm .4 \pm .6) \times 10^{-8}$	200	E787 (1997)	**PRL 79**:4756
$K^+ \to \pi^+\mu^+\mu^-$	$(9.22 \pm .60 \pm .49) \times 10^{-8}$	430	E865 (2000)	**PRL 84**:2580
$K^+ \to \pi^+e^+e^-\gamma$	—	∼30	E865 (1999)	DPF99
	$\mathbf{K}_{\pi 2\gamma}$			
$K^+ \to \pi^+\pi^\circ\gamma$ (DE)	$(4.72 \pm .77 \pm .28) \times 10^{-6}$	360	E787 (2000)	**PRL 85**:4856
	$\mathbf{K}_{\ell 4}$			
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.11 \pm .01 \pm .11) \times 10^{-5}$	388,270	E865 (2001)	**PRL 87**:221801
$K^+ \to \pi^+\pi^-e^+\nu_e\gamma$	—	obs.	E865 (2001)	priv. comm.
	$\mathbf{K}_{\ell 2\gamma}$			
$K^+ \to \mu^+\nu_\mu\gamma$ (SD)	$(1.33 \pm .12 \pm .18) \times 10^{-5}$	2588	E787 (2000)	**PRL 85**:2256
$K^+ \to \mu^+\nu\mu^+\mu^-$	$< 4.1 \times 10^{-7}$	0	E787 (1989)	**PRL 63**:2177
$K^+ \to e^+\nu\mu^+\mu^-$	$< 5.0 \times 10^{-7}$	0	E787 (1998)	**PRD 58**:012003
$K^+ \to e^+\nu\mu^+\mu^-$	—	obs.	E865 (2001)	priv. comm.
$K^+ \to \mu^+\nu e^+e^-$	$(6.84 \pm .40) \times 10^{-8}$	∼1500	E865 (2000)	priv. comm.
$K^+ \to e^+\nu e^+e^-$	$(2.60 \pm .15) \times 10^{-8}$	∼400	E865 (2000)	priv. comm.
	searches beyond the standard model			
$K_L^\circ \to \mu e$	$< 4.7 \times 10^{-12}$	—	E871 (1998)	**PRL 81**:5734
$K^+ \to \pi^+\mu^+e^-$	$< 2.8 \times 10^{-11}$	—	E865 (2000)	**PRL 85**:2450
$K^+ \to \pi^+X^\circ$	$< 1.1 \times 10^{-10}$	—	E787 (2000)	**PRL 84**:3768
$K^+ \to \pi^-\mu^+\mu^+$	$< 3.0 \times 10^{-9}$	—	E865 (2000)	**PRL 85**:2877
$K^+ \to \pi^-e^+e^+$	$< 6.4 \times 10^{-10}$	—	E865 (2000)	**PRL 85**:2877
$K^+ \to \pi^+\mu^-e^+$	$< 5.2 \times 10^{-10}$	—	E865 (2000)	**PRL 85**:2877
$K^+ \to \pi^-\mu^+e^+$	$< 5.0 \times 10^{-10}$	—	E865 (2000)	**PRL 85**:2877
$K^+ \to \pi^+\gamma$	$< 3.6 \times 10^{-7}$	—	E787 (2001)	sub. to PRD

CKM Matrix and CP-Violation

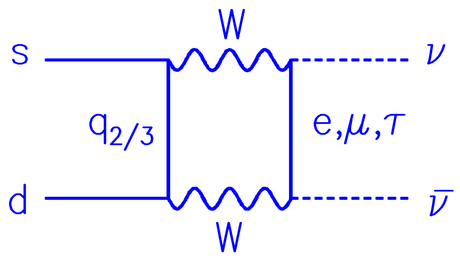
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\overline{\rho}-i\overline{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta})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

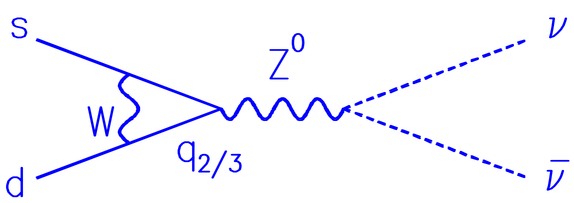
$$\overline{\rho} = \rho(1-\frac{\lambda^2}{2}) \qquad \overline{\eta} = \eta(1-\frac{\lambda^2}{2})$$

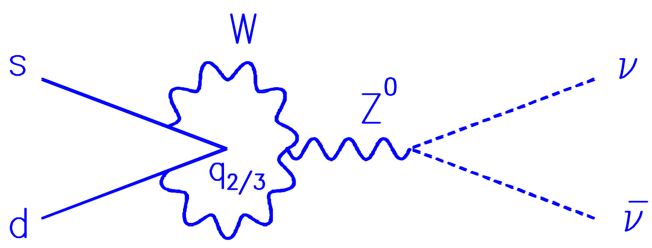
$K\to\pi\nu\overline{\nu}$: The Golden Modes

- $K^+\to\pi^+\nu\overline{\nu}$: measure $|\lambda_t| \equiv |V_{ts}^* V_{td}\,|$.
- $K_L^\circ\to\pi^\circ\nu\overline{\nu}$: direct CP violating, measure $Im(\lambda_t) = Im(V_{ts}^* V_{td}\,)$.

This is the best way to measure $Im(\lambda_t)$ and the Jarlskog invariant J_{CP}.





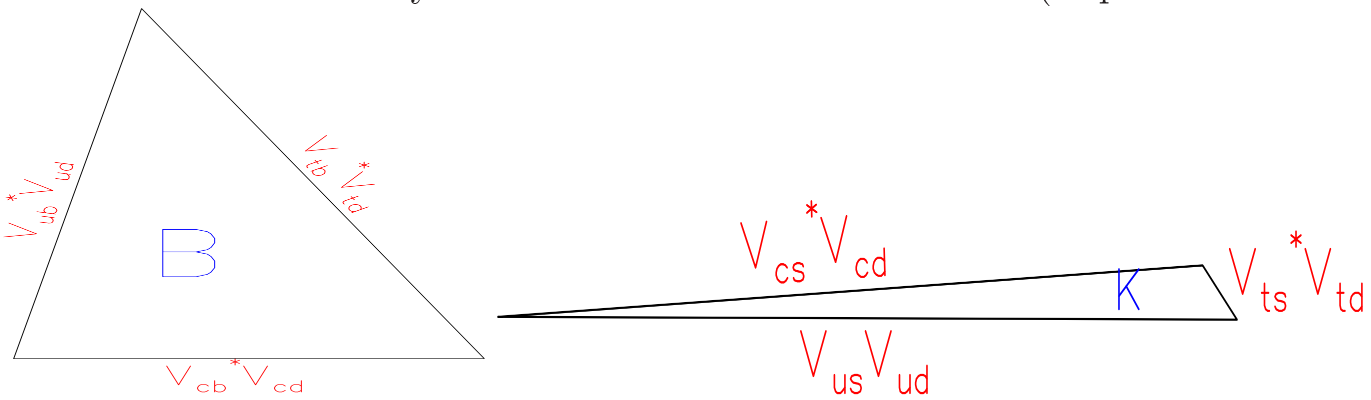


Combining the two **Golden Kaon Modes** **($K\to\pi\nu\overline{\nu}$)** with the two **Golden B Modes ($B_d^\circ\to\psi K_S^\circ$ and $\Delta M_{B_s}/\Delta M_{B_d}$)**, two important tests of SM CP violation can be made:

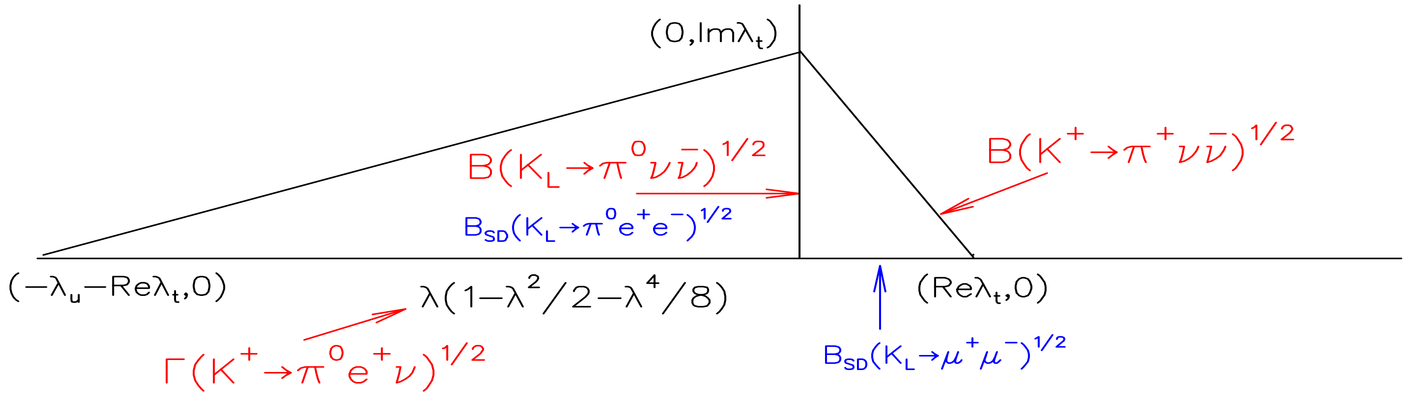
- Overconstraint of $|V_{td}|$ from $K^+\to\pi^+\nu\overline{\nu}$ and $\Delta M_{B_s}/\Delta M_{B_d}$
- Overconstraint of β from $K_L^\circ\to\pi^\circ\nu\overline{\nu}$ $/K^+\to\pi^+\nu\overline{\nu}$ and $B_d^\circ\to\psi K_S^\circ$

Rare Kaon Decays and the CKM Matrix

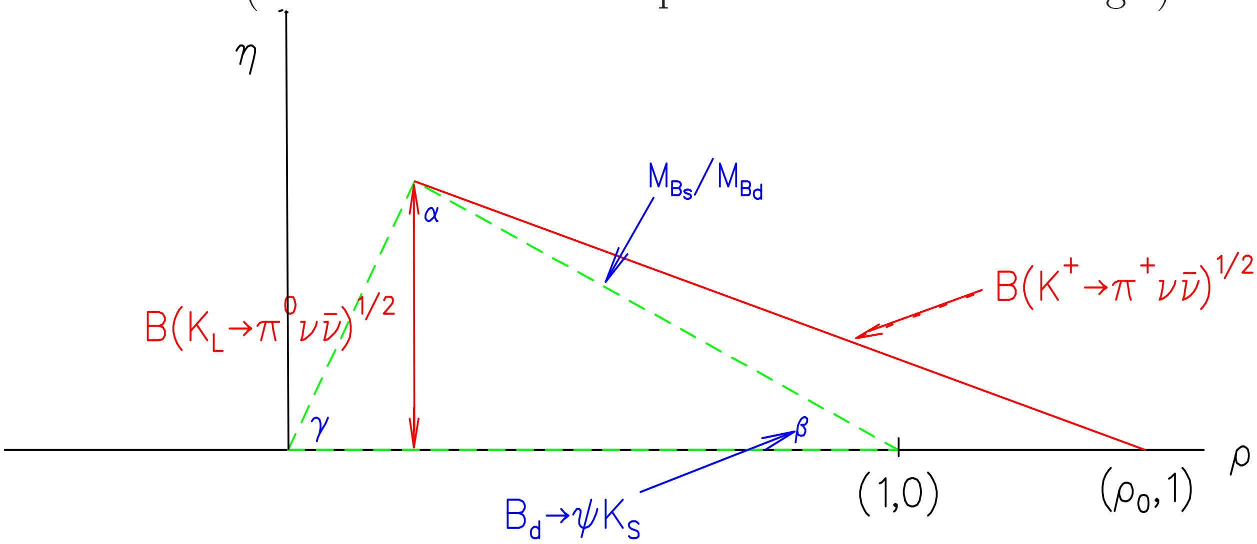
There are six unitarity relations: all should be tested (requires 3 measurements).



The fundamental measure of CP violation, J_{CP} is related to the area of the triangle and should be measured as well as possible (in as many ways as possible). In the kaon triangle, only two measurements are needed to determine the area: $K^+ \to \pi^\circ e^+ \nu_e$ and $K_L^\circ \to \pi^\circ \nu \overline{\nu}$; and we can completely determine the unitarity triangle with theoretically unambiguous measurements:.



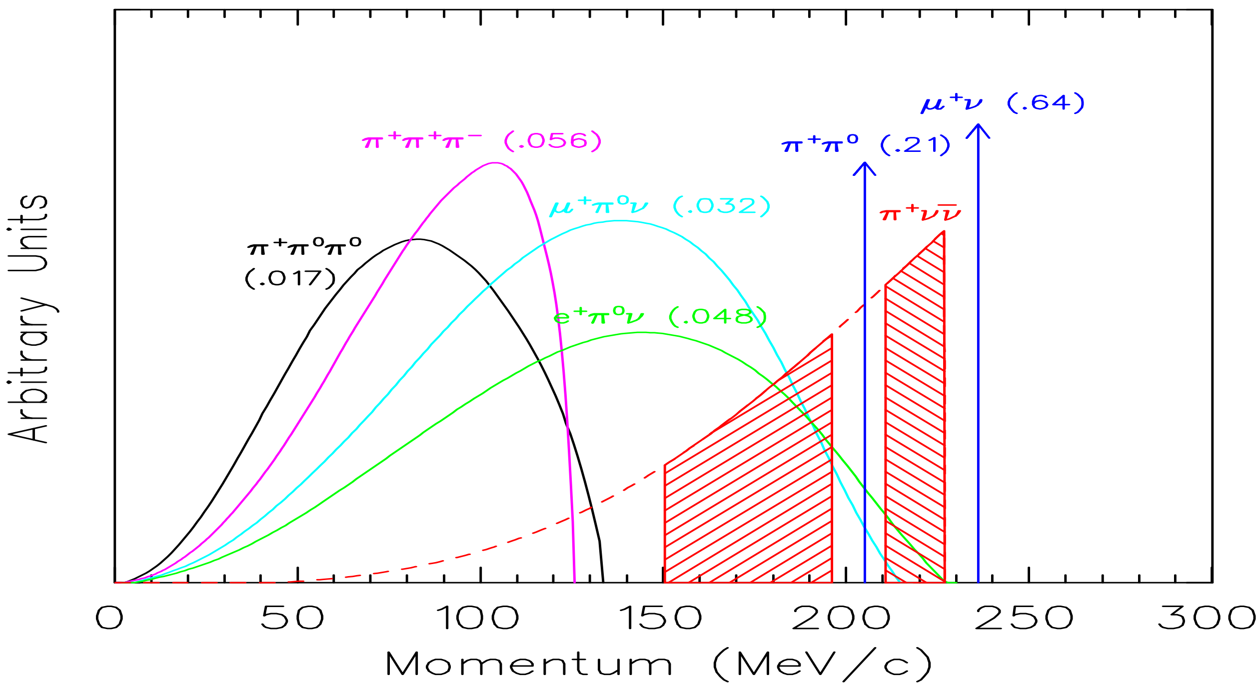
Using only those modes with little or no theoretical ambiguity there are 4 constraints on the two variables (in the conventional representation of the triangle):



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

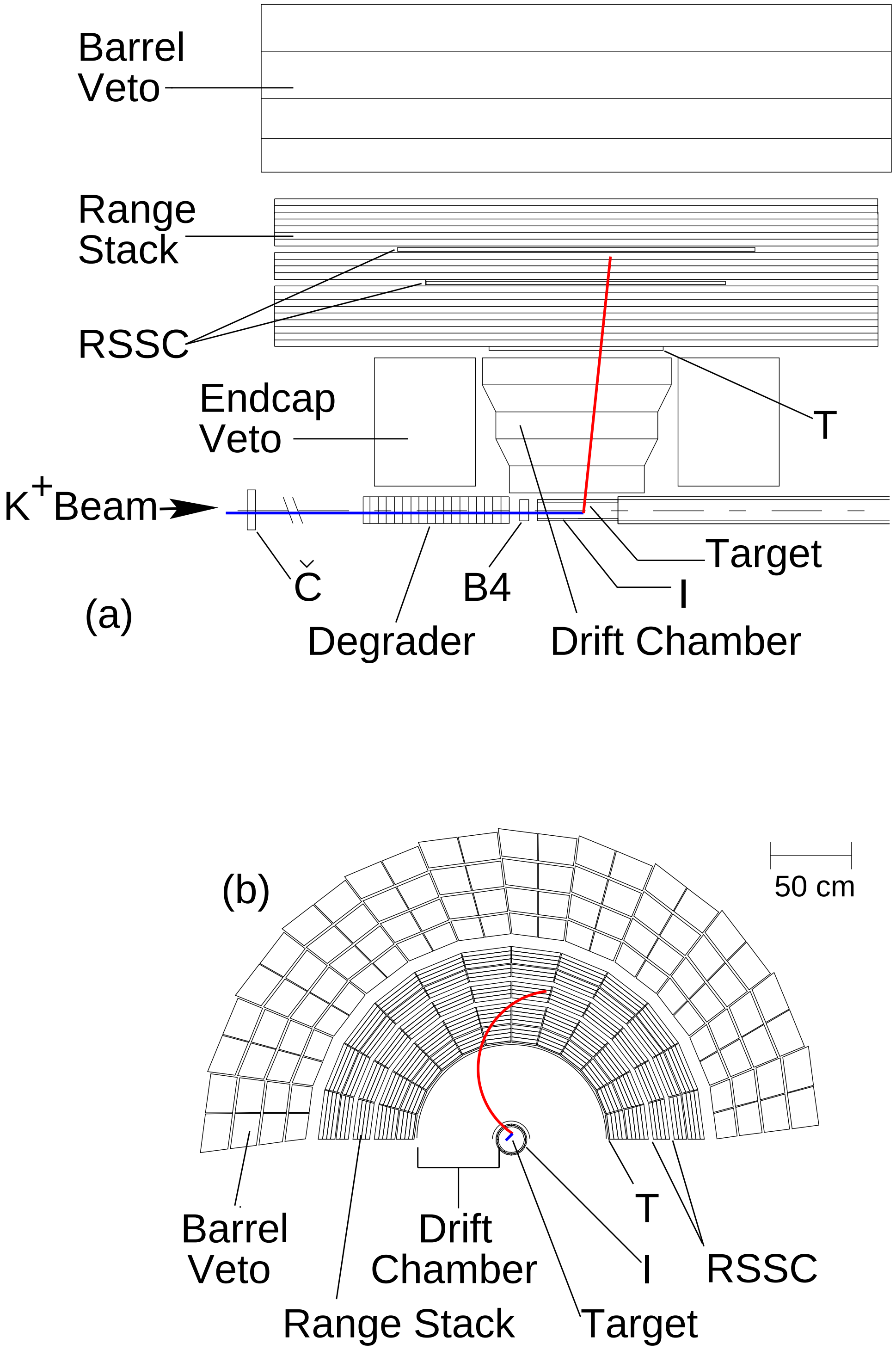
Measure everything possible

- Positively identify π^+.
- Veto extra particles.
- Measure kinematics with high resolution and redundancy.



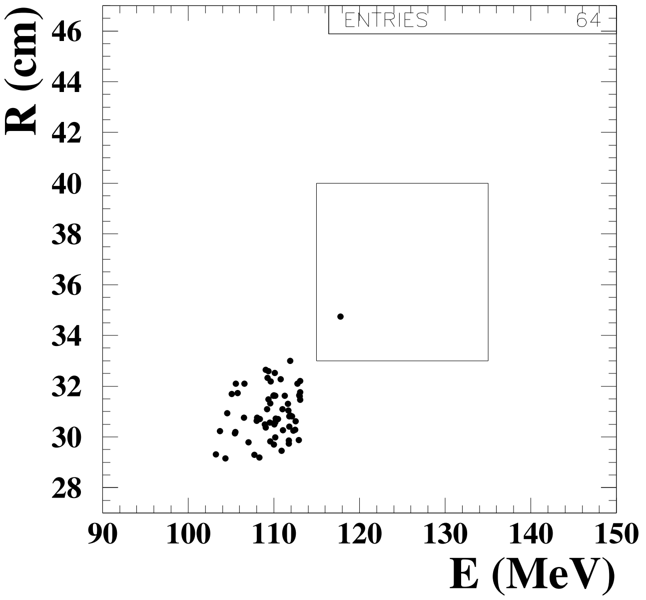
- Suppress background by 10^{11}: B/S(SM) < 0.1
- Reliably **measure** background from data.

E787 Spectrometer

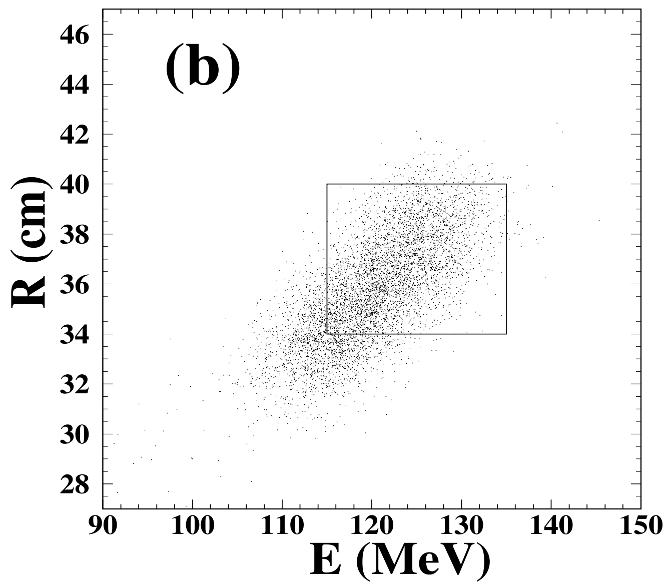


$K^+ \to \pi^+ \nu \overline{\nu}$ Event

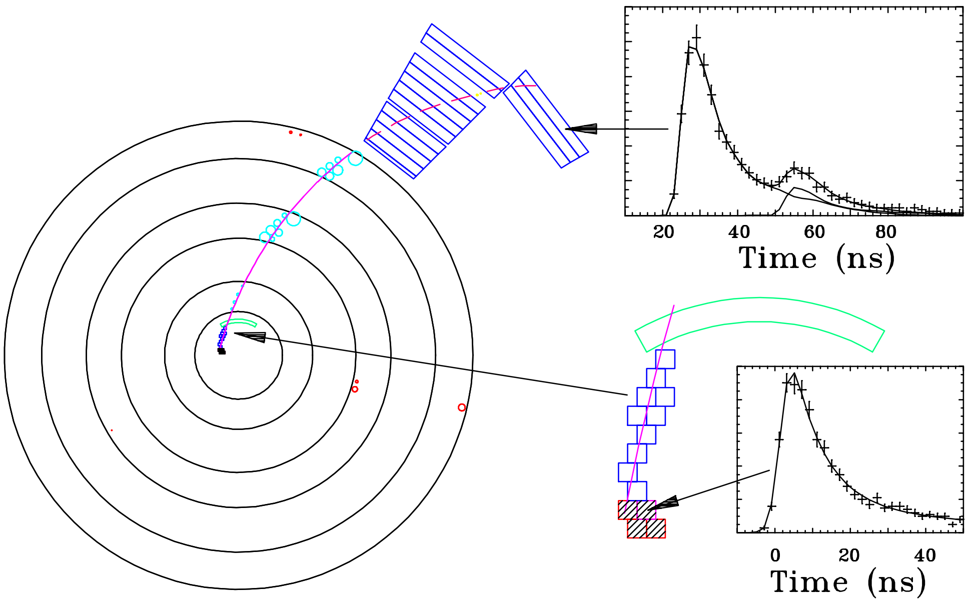
1995–97 Data



Monte Carlo



Event Display



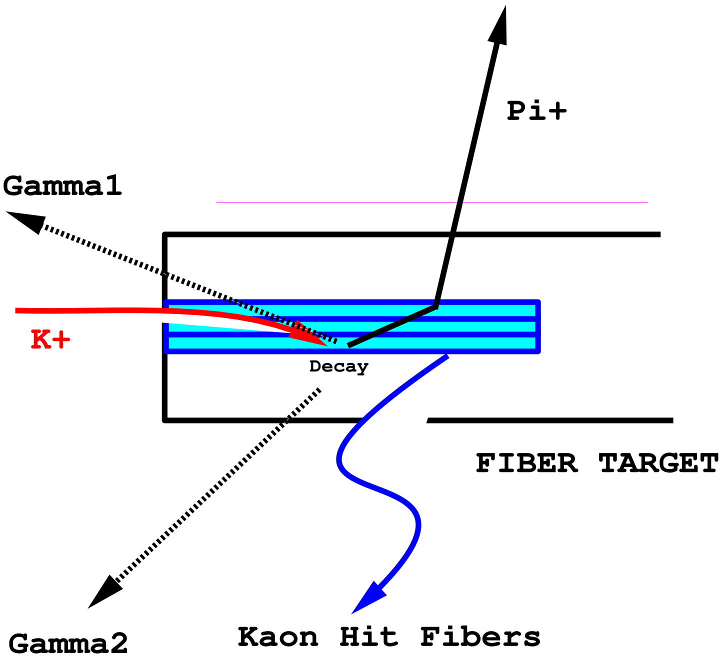
$$\mathbf{BR}(K^+ \to \pi^+ \nu \overline{\nu}\ ) = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$

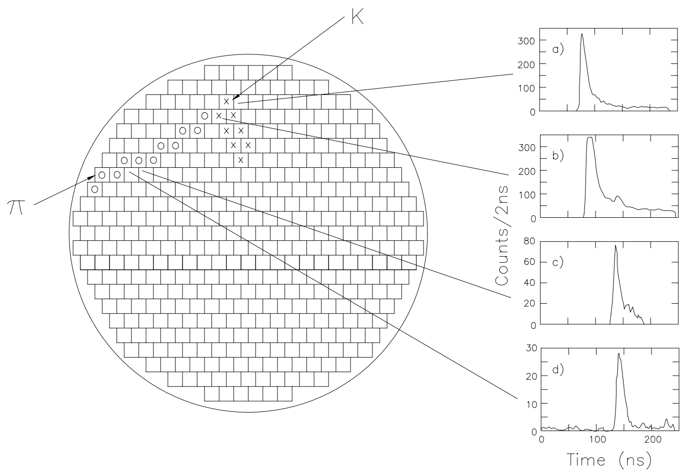
SM: BR($K^+ \to \pi^+ \nu \overline{\nu}$) $= 0.75 \pm 0.29 \times 10^{-10}$ (from CKM fits)

[1995: PRL **79**, 2204 (1997), 1995–7: PRL **84**, 3768 (2000)]

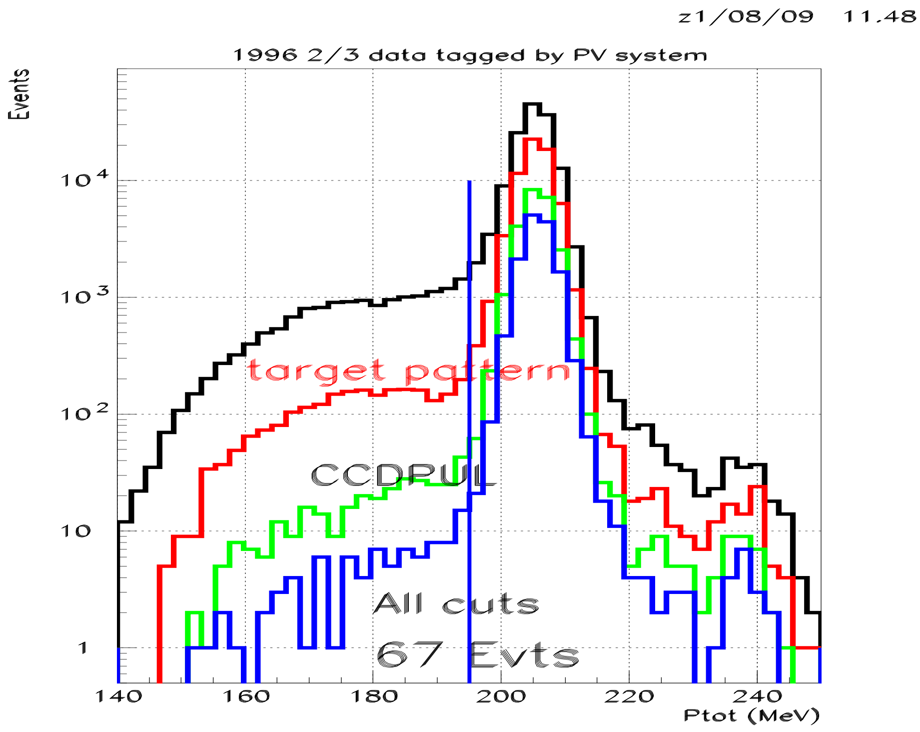
$\pi\nu\overline{\nu}(2)$ (below $K^+ \to \pi^+\pi^\circ$) data analysis

- Much larger phase space acceptance below Kpi2 peak.
- Large background from $K^+ \to \pi^+\pi^\circ$ in which π^+ undergoes interaction in the scintillator fiber target.
- After reconstruction of pion and kaon, make fits to all CCD pulses for kaon fibers.
  - Find second pulses at pion time overlapping kaon fibers. Cut at 1 MeV threshold.
  - Measure rejection of CCD cut by using events tagged by photons.
  - Measure Photon veto rejection by using events tagged by CCD second pulses as well as kinks in the track.

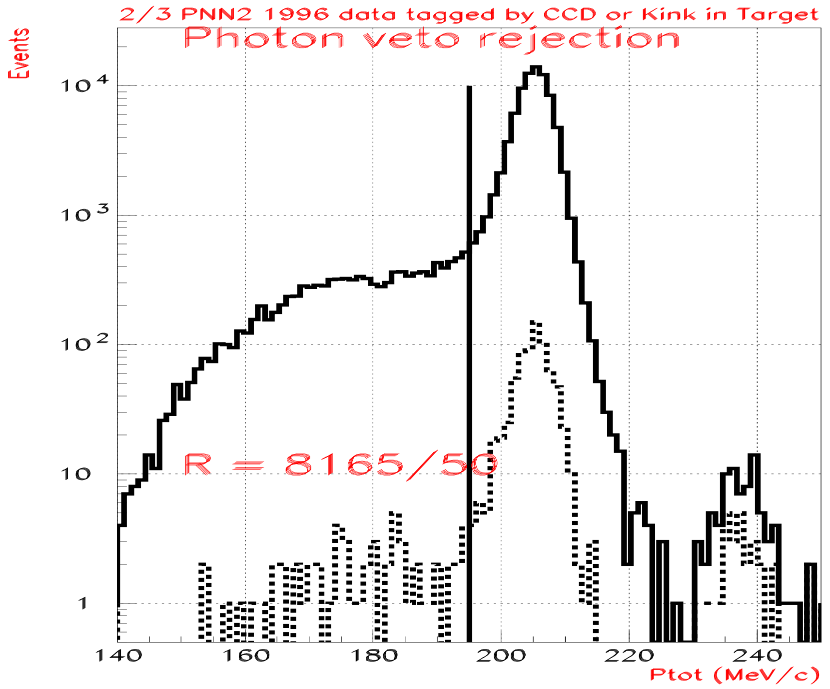




Kpi2 background



$$\mathbf{N\ =\ 67}$$



$$\mathbf{Rej}(\overline{\gamma})\ =\ 163 \pm 23$$

$$N_{b.g.} = 1.5 \times N_{Kin.}/R_{\bar{\gamma}} = 0.62$$

$\pi\nu\overline{\nu}$(2) Background Estimate

Table of Backgrounds for PNN2 data

Background	
$K_{\pi 2}$ scatter (target)	0.62 ± 0.17
$K_{\pi 2}$ scatter (RS)	0.007 ± 0.006
$K^+ \to \pi^+ \pi^\circ \gamma$	0.027 ± 0.004
$K^+ \to \mu^+ \nu_\mu \gamma$	0.007 ± 0.007
1-beam	0.0003 ± 0.0003
2-beam	0.033 ± 0.033
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	0.026 ± 0.032
Charge Exchange	0.011 ± 0.011
Total	0.731 ± 0.177

Acceptance factors

	PNN2	PNN1
KB_L	1.2×10^{12}	
A_{UMC}	0.0808 ± 0.001	0.033
A_{KM21}	0.0401 ± 0.0005	0.397
A_{TD}	0.5448 ± 0.0040	0.270
A_{KIN}	0.6741 ± 0.003	0.775
A_{tot}	0.0012 ± 0.0002	0.0027

The large loss due to CCD and tighter photon vetos (A_{KM21}) will be improved the analysis of remaining data as well as E949.

Final result coming soon.

from Milind V. Diwan

Results from 1995–98 $\pi\nu\overline{\nu}(1)$ data sets

Background	1995–97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam (1 + 2)	0.02 ± 0.02	0.004 ± 0.001
CEX	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total background	0.08 ± 0.02	$0.066^{+0.044}_{-0.025}$

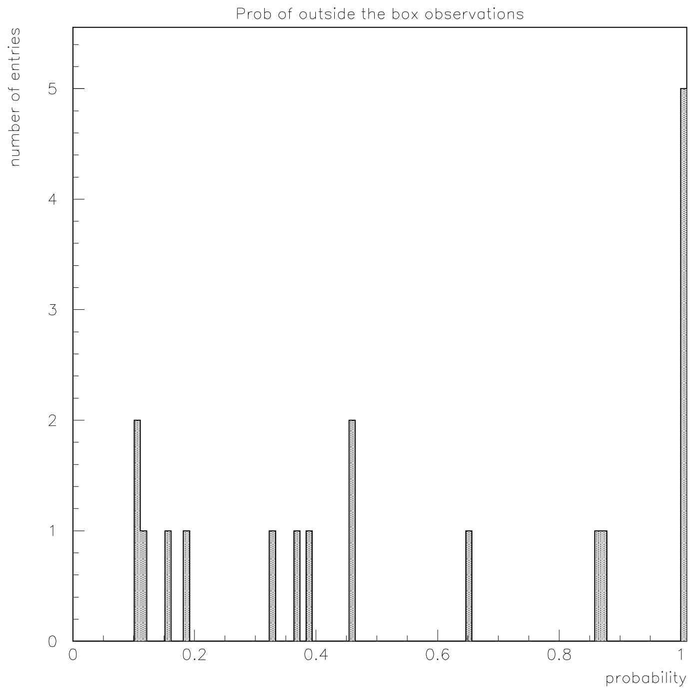
Acceptance factors	1995–97	1998
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ nucl. int., decay-in-flight	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi - \mu - e$ decay acceptance	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.00196

Summary	1995–97	1998
$\mathrm{N_K}$	3.2×10^{12}	2.7×10^{12}
Acc.	0.0021(1)(2)	0.00196(5)(10)
Sensitivity	1.5×10^{-10}	1.89×10^{-10}
Background	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

Examination "outside the box"

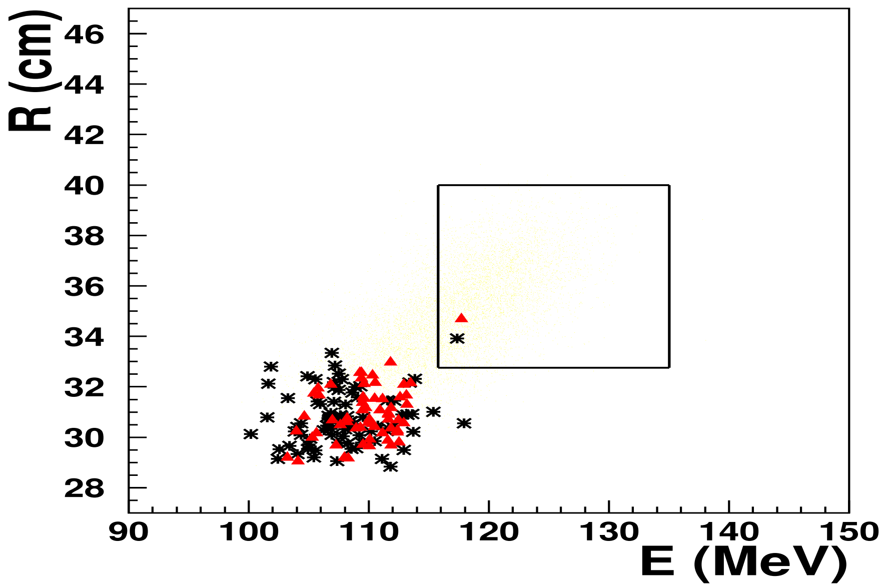
To confirm the validity of the background estimation technique, predicted background outside the signal region is compared to observation by loosening the primary cuts for each background.

		Looser cuts $\longrightarrow$			
$K^+ \to \pi^+\pi^\circ$	predict	1.18	4.74	33.00	225.00
	observe	3	5	36	233
$K^+ \to \mu^+\nu_\mu$ "tail"	predict	0.33	23.67	66.44	204.00
	observe	0	30	66	205
$K^+ \to \mu^+\nu_\mu$ "band"	predict	0.21	5.64	32.82	118.00
	observe	1	7	36	118
1-beam K	predict	0.029	0.578	4.188	
	observe	0	2	8	
2-beam K	predict	0.007	0.059	0.398	
	observe	0	0	0	

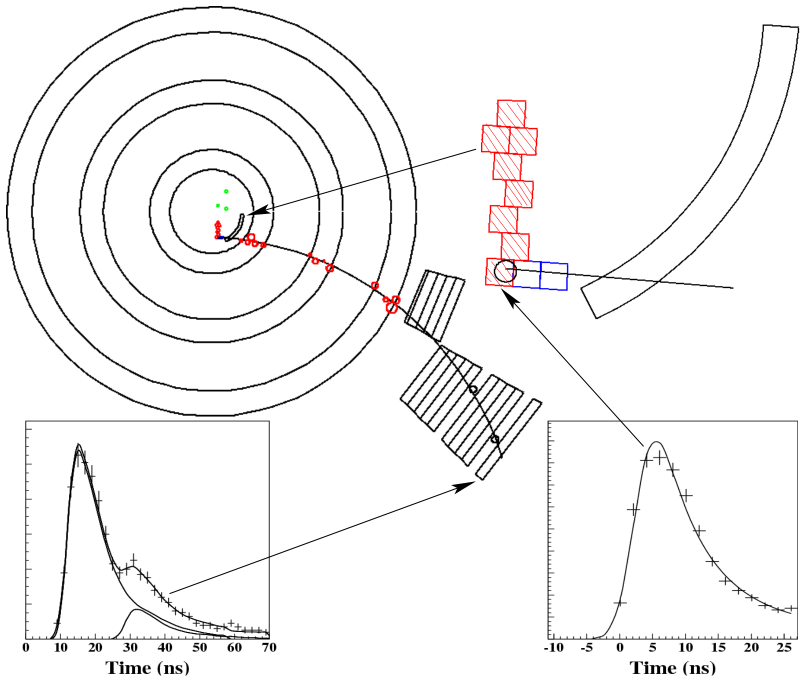


$K^+ \to \pi^+ \nu\overline{\nu}$ Events

1995–98 Data



Event Display (1998)

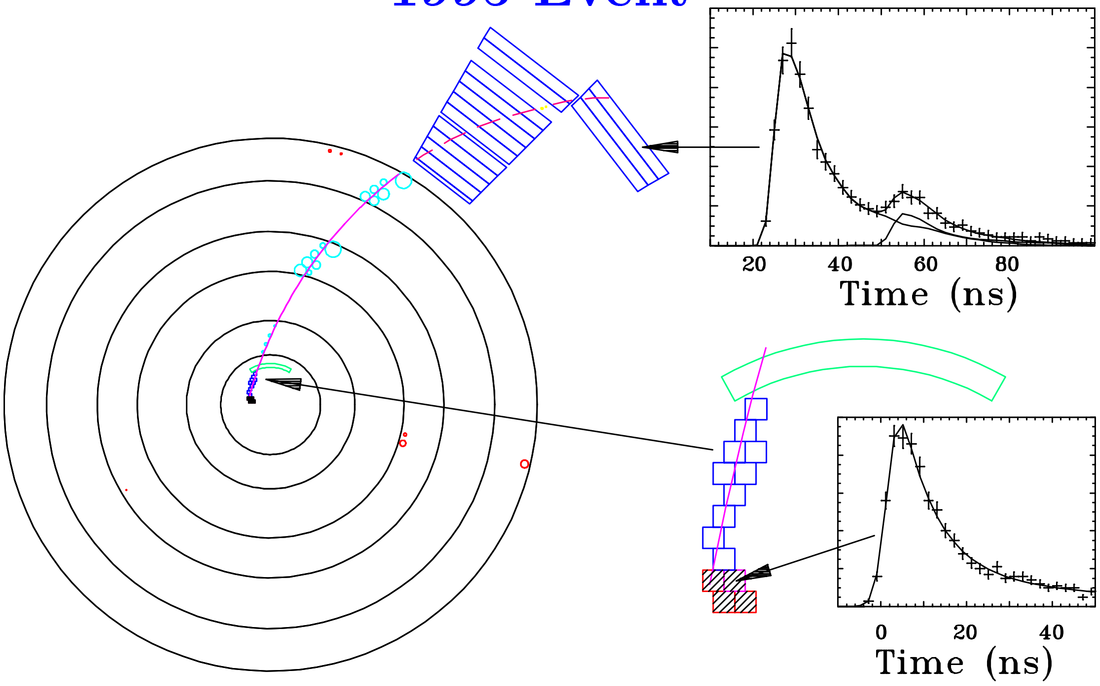


$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

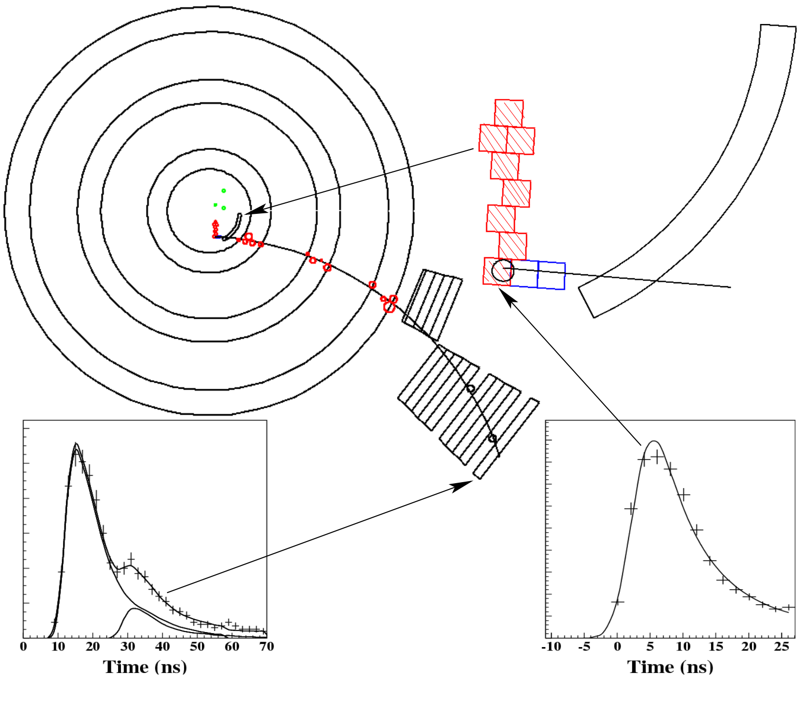
[1995: PRL **79**, 2204 (1997), 1995–7: PRL **84**, 3768 (2000), 1995–8: sub. to PRL]

The Two E787 $K^+ \to \pi^+ \nu\overline{\nu}$ Events

1995 Event



1998 Event

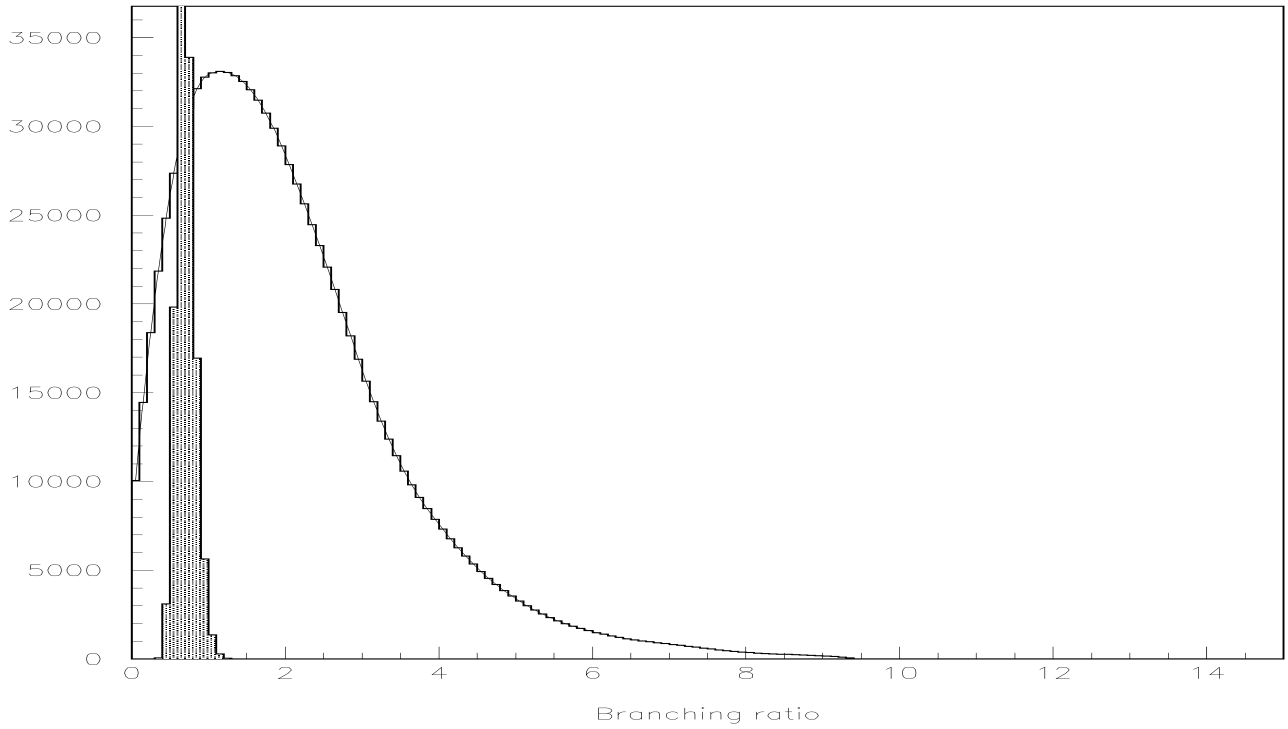


$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

[1995: PRL **79**,2204 (1997), 1995–7: PRL **84**,3768 (2000), 1995–8: sub. to PRL]

Comparison of B($K^+ \to \pi^+ \nu\bar{\nu}$) to SM

Event	Kinematic quantities $P(MeV/c)$	$R(cm)$	$E(MeV)$	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

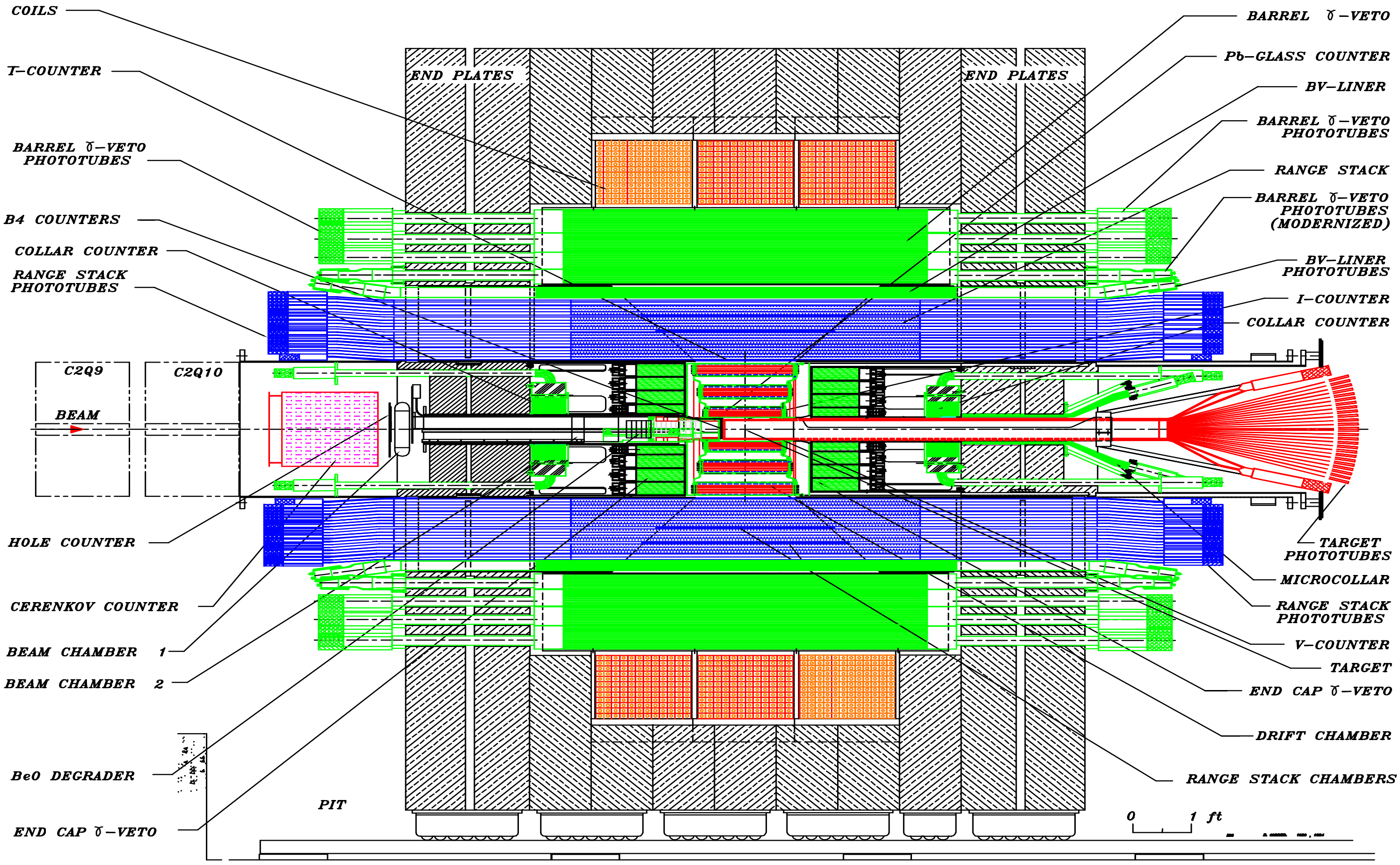
- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$ (SM: $0.75 \pm 0.29 \times 10^{-10}$)

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

- $P_b \sim 0.02\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% CL)

E949: Measurement of B($K^+ \to \pi^+ \nu\bar{\nu}$)

Alberta/BNL/FNAL/Fukui/IHEP/INR/KEK/Kyoto/UNM/Osaka/TRIUMF



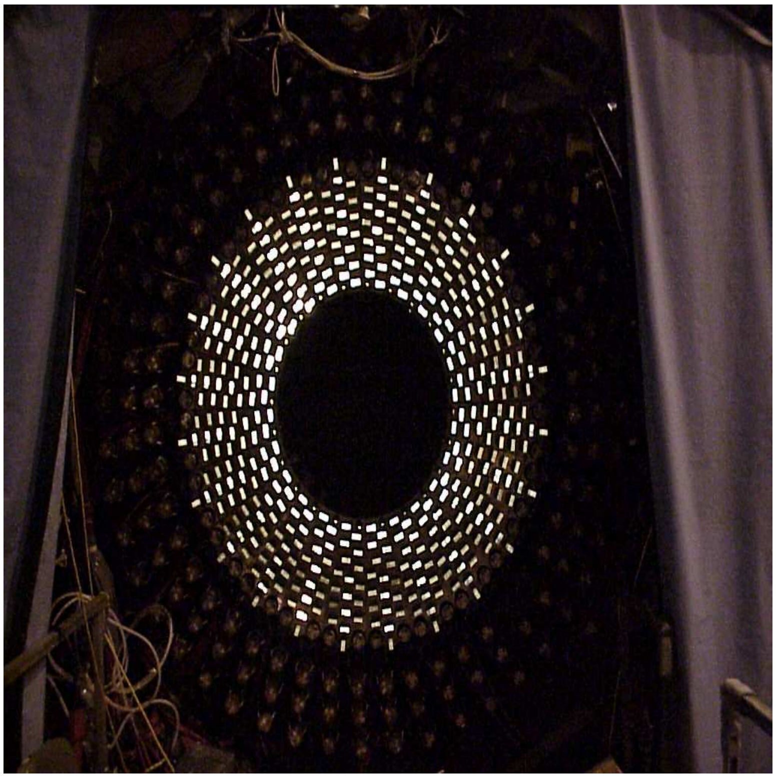
Sensitivity improvement with respect to E787 (1995):

- Increased spill length (×1.56)
- Lower Momentum (×1.38)
- Increased efficiency (trigger,DAQ,analysis) (×3.2)
- Acceptance below $K_{\pi 2}$ peak [×2]
- Total gain of ×7 – [14] (per hour of running)

⟹ Will observe 5–10 SM events in 2 years.

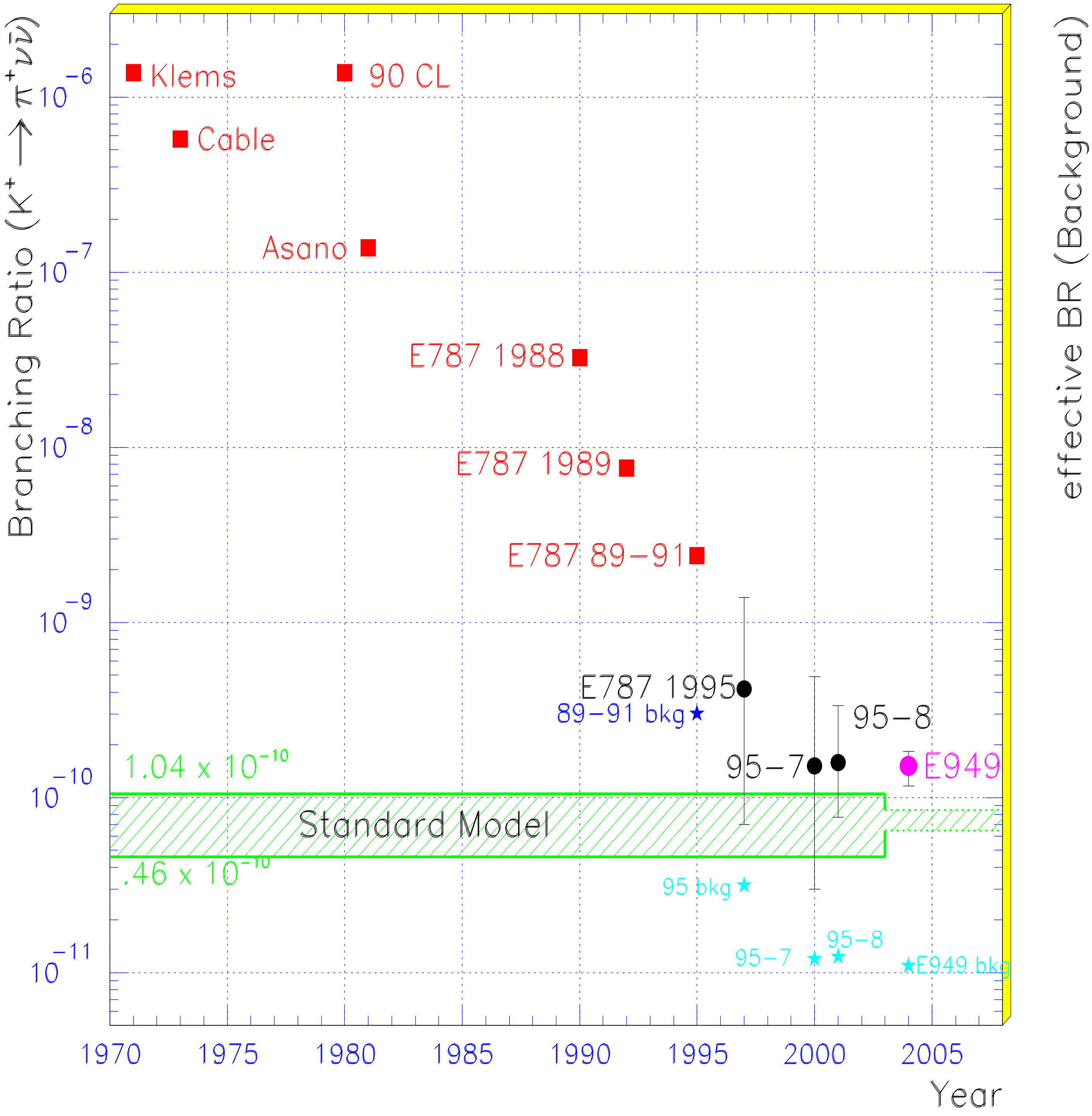
E949 Upgrades

- AGS remains the world's highest intensity proton synchrotron
- 6.5×10^{13} protons/spill to increase duty factor and lower kaon momentum
- Proven technique and background rejection from E787.
- Detector and beam upgrades to improve efficiency and bkg rej.
- Beam upgrades to improve reliability and cope with large flux

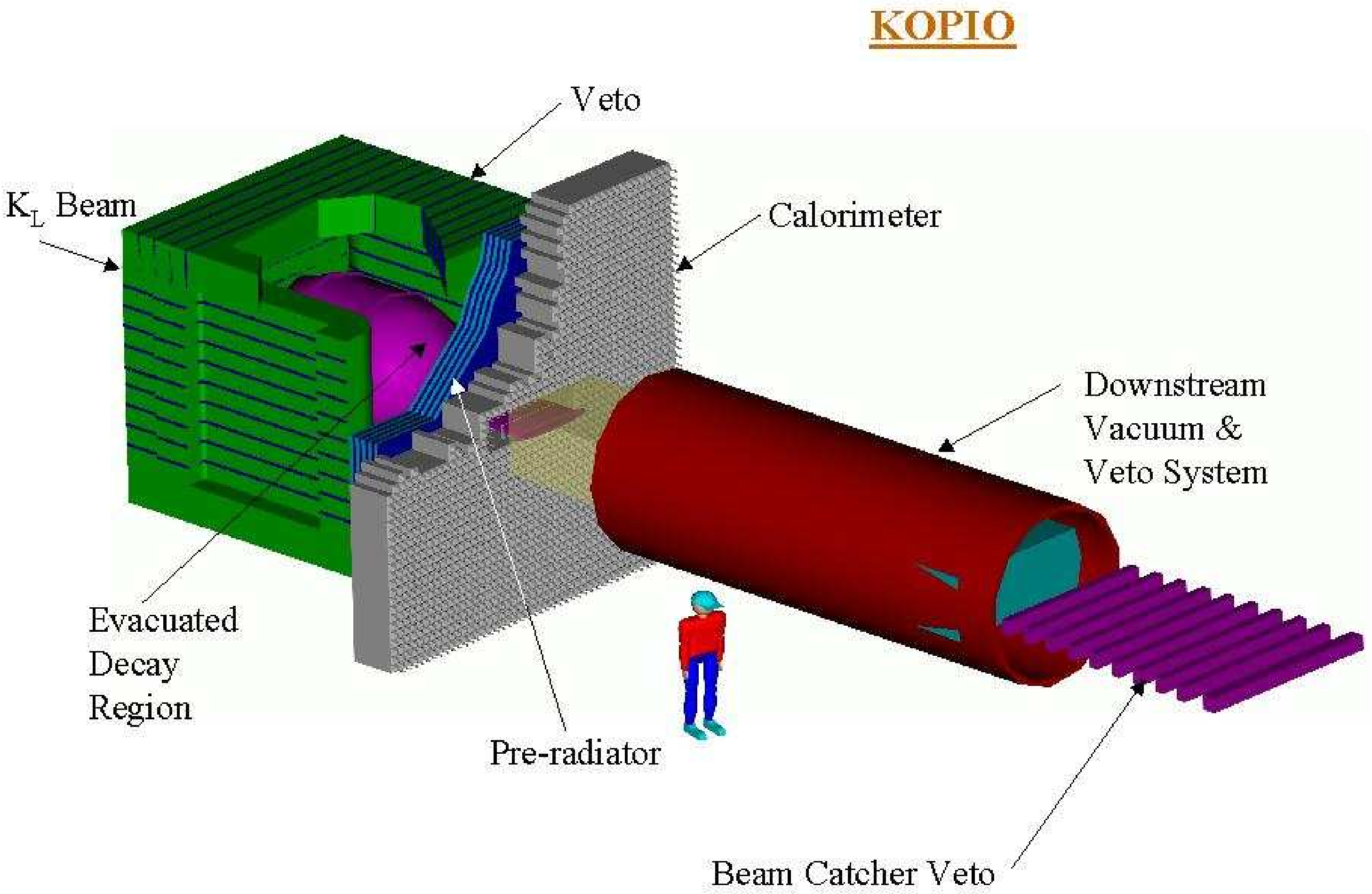


- **Photon Veto (access low p_π phase space)**
  - **Barrel Veto Liner (additional 2.3 $X_\circ$)** *Completed*
  - **Live degrader upgrade** *Completed*
  - **Additional upstream vetoes** **11/01**
  - **Thicken collar counter downstream** *Completed*
  - **Downstream veto** *Completed*
- **UTC (tracking efficiency increase)** *Completed*
- **Range stack upgrades**
  - **Replace T-counters (better trigger, tracking efficiency)** *Completed*
  - **Replace Layer 2-5 (better dE/dx resolution, timing)** *Completed*
  - **Repair dead RSSCs (better tracking efficiency)** *Completed*
  - **Upgrade RSSC electronics (muon rejection)** **11/01**
  - **Monitor system (reliability and energy resolution)**
    - **LEDs on RS** *Completed*
    - **Voltage monitor** *Completed*
- **Trigger upgrade (reduce deadtime and improve rejection)** **mostly completed**
- **DAQ upgrade (reduce deadtime, increase rate capability)** **mostly completed**

History of the Search for $K^+ \to \pi^+ \nu \overline{\nu}$



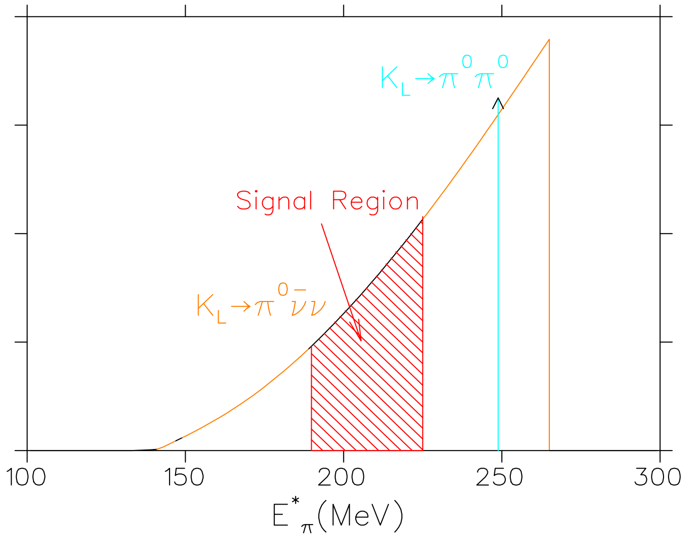
KOPIO: $K_L^\circ \to \pi^\circ \nu \overline{\nu}$

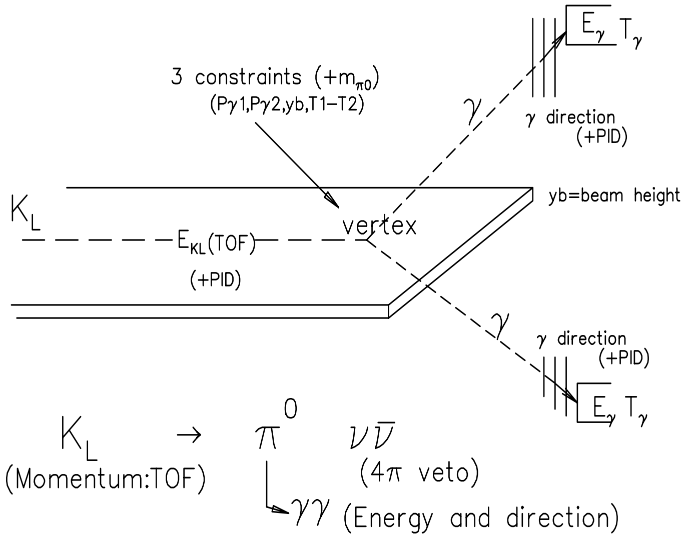


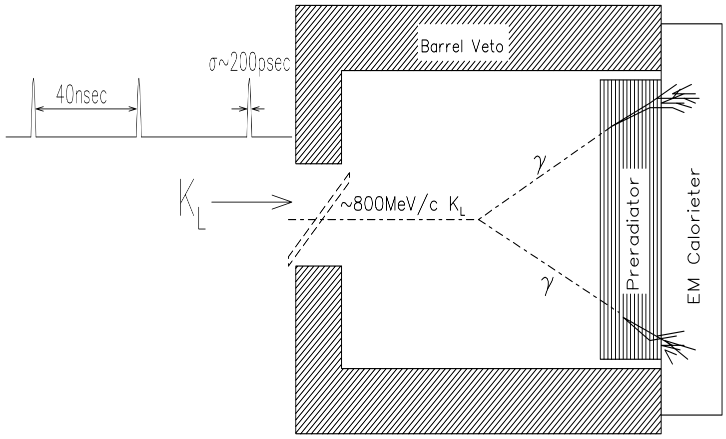
UBC/BNL/Cincinnati/INR/Kyoto/UNM
TJNAF/TRIUMF/VPI/Yale/Zurich

- **Goal:**
  - **Measure BR to ~15% $\longrightarrow$ $\Delta\eta$ ~7–8%**
- **Sensitivity & Backgrounds**
  - ~65 events/9000 hr (BR $= 3\times10^{-11}$)
  - Background 30 events (mainly $K_L^\circ \to \pi^\circ\pi^\circ$).

KOPIO Principles and Technique







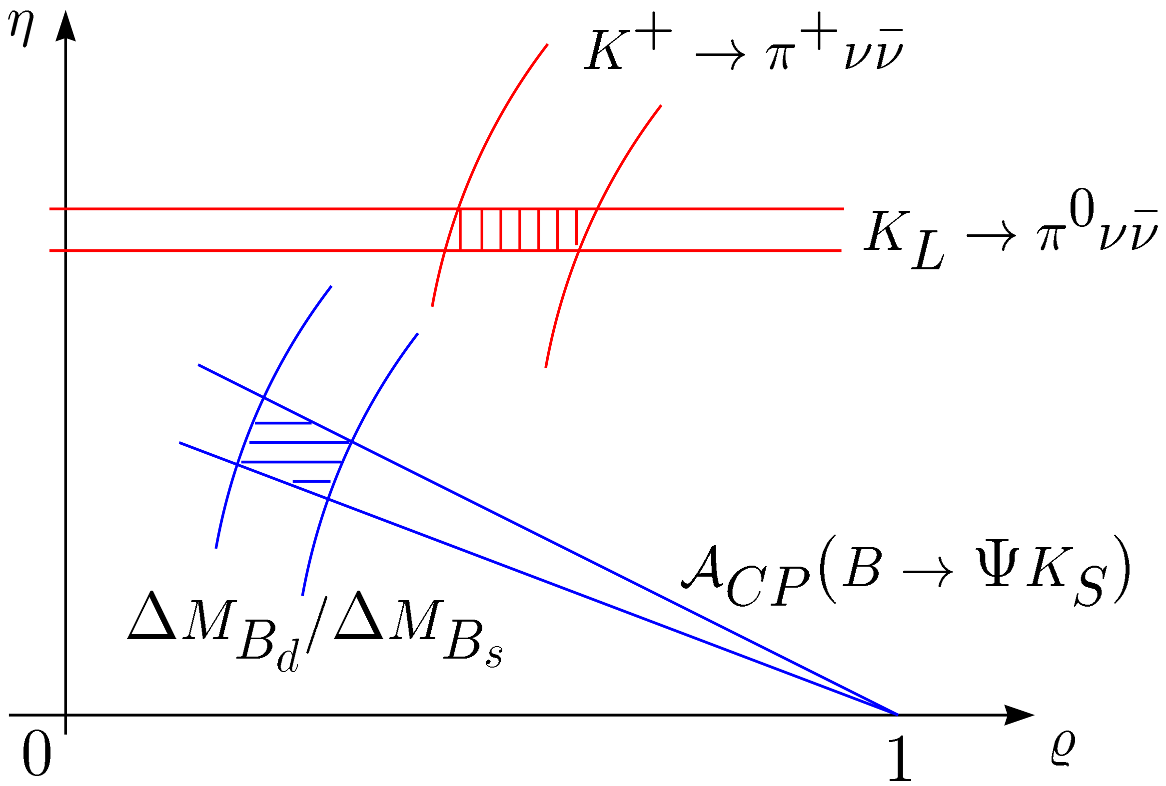
- Measure all initial & final state quantities.
  - Work in the K_L center of mass: Bunched, large angle (low $\vec{p}$) beam.
  - Preradiator to measure γ directions.
  - Calorimeter for energies and times.
- *Measure* backgrounds.
- Hermetic photon veto ('beam catcher').

- Bunched beam
  $\longrightarrow$ kinematically reduce $K_L^\circ \to \pi^+\pi^-$ by ~40, most neutrons and accidental K° out of time, measure π° momentum spectrum (consistent with $K_L^\circ \to \pi^\circ \nu\overline{\nu}$).
- Low momentum beam
  $\longrightarrow$ neutrons below π° threshold, no hyperons, neutrons and photons out of time.
- Determine decay vertex
  $\longrightarrow$ 4C fit to π°, decay vertex in plane, reduce adcidentals.

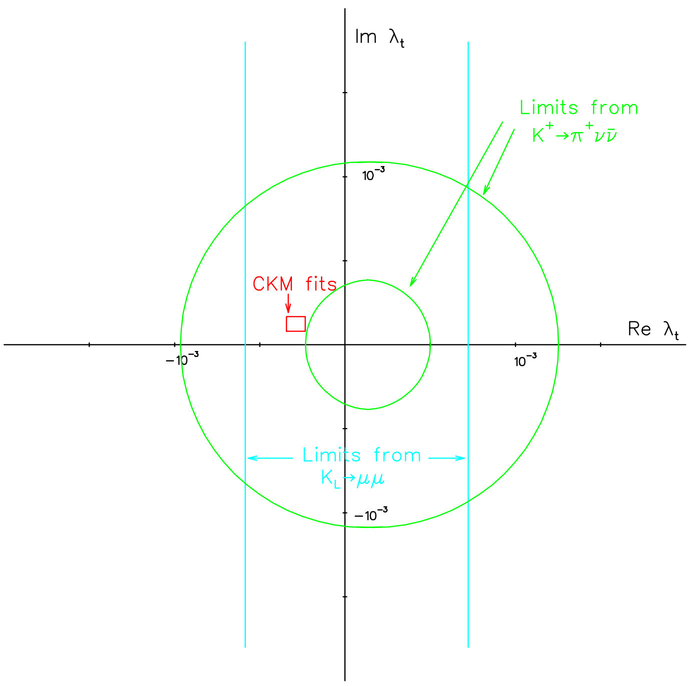
Future Kaon contribution to the CKM Matrix

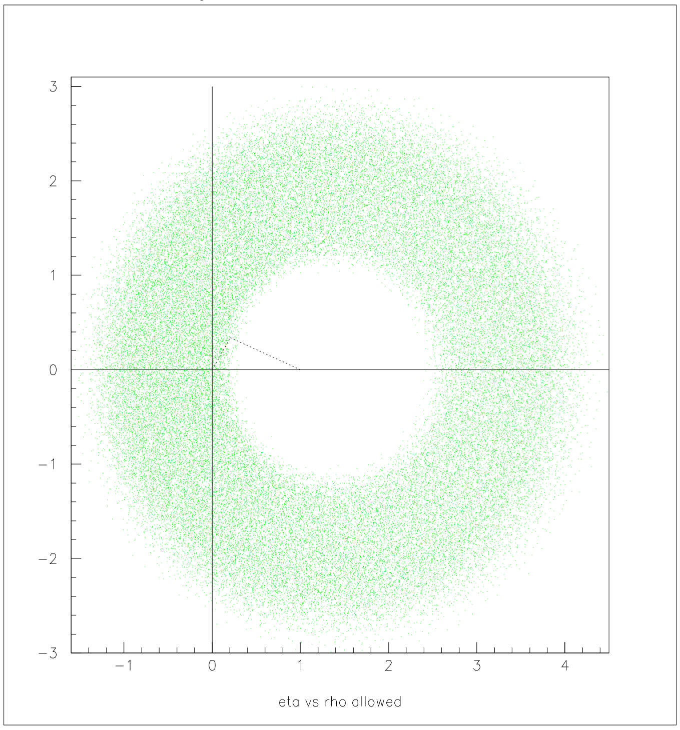
Measurements and tests of the Standard Model:

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



Expressed in terms of λ_t:





Conclusions

- $K^+ \to \pi^+ \nu\overline{\nu}$
  - $K^+ \to \pi^+ \nu\overline{\nu}$ has been observed! (2 events)

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

$$0.007 < |V_{td}| < 0.030$$

$$2.9 \times 10^{-4} < |\lambda_t \equiv V^*_{ts} V_{td}| < 1.2 \times 10^{-3}$$

$$-0.88 \times 10^{-3} < Re(\lambda_t) < 1.2 \times 10^{-3}$$

$$Im(\lambda_t) < 1.0 \times 10^{-3}$$

- $K^\circ_L \to \pi^\circ \nu\overline{\nu}$
  - Direct search for $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ needs $\mathcal{O}(10^4)$ improvement (Indirect limit within $\times 100$ of SM).
  - KEK E391a plans to reach to within $\times$10 in $\sim$5 years..
  - KOPIO plans for 100 SM events in <10 years.

- Future
  - Future prospects for $K^+ \to \pi^+ \nu\overline{\nu}$ and $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ are bright.
  - Expect sensitivity to 10 SM $K^+ \to \pi^+ \nu\overline{\nu}$ events within 3 years.
  - ...maybe 20 non-SM $K^+ \to \pi^+ \nu\overline{\nu}$ events.
  - Should observe $\sim$100 SM events in both modes in <10 years (CKM,Kopio).
  - Combined with new results in the B system (Belle, Babar, CDF) will allow critical tests of the SM picture of quark mixing and CP-violation from comparison of B's and K's.