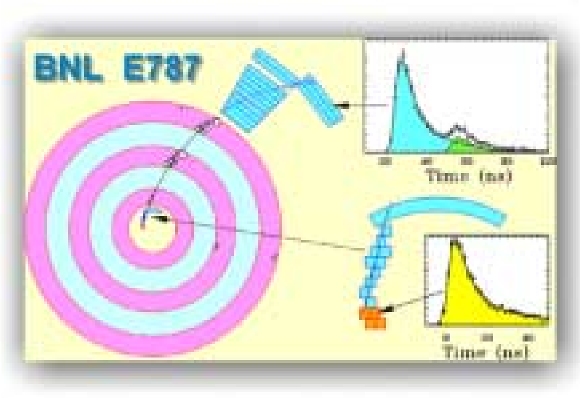


CIPANP
Quebec City
May 22–28, 2000

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

- Overview of $K^+ \to \pi^+ \nu\overline{\nu}$
- Status of the E787 search.
- Future: E949, CKM

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BROOKHAVEN NATIONAL LABORATORY

# CKM Matrix and CP-Violation

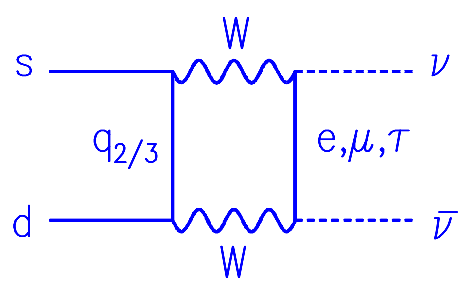
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\overline{\rho}-i\overline{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta})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

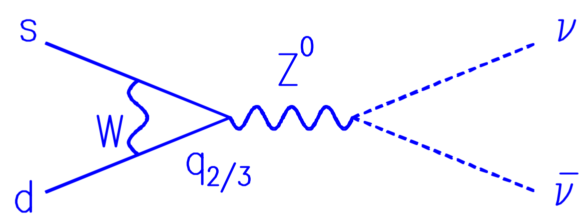
$\overline{\rho} = \rho(1-\frac{\lambda^2}{2}) \qquad \overline{\eta} = \eta(1-\frac{\lambda^2}{2})$

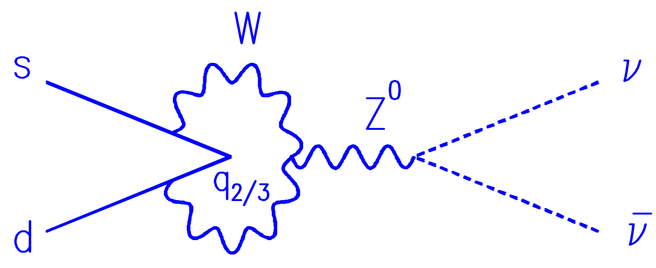
## $K \to \pi\nu\overline{\nu}$ : The Golden Modes

- $K^+ \to \pi^+\nu\overline{\nu}$ : 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 $J_{CP}$.

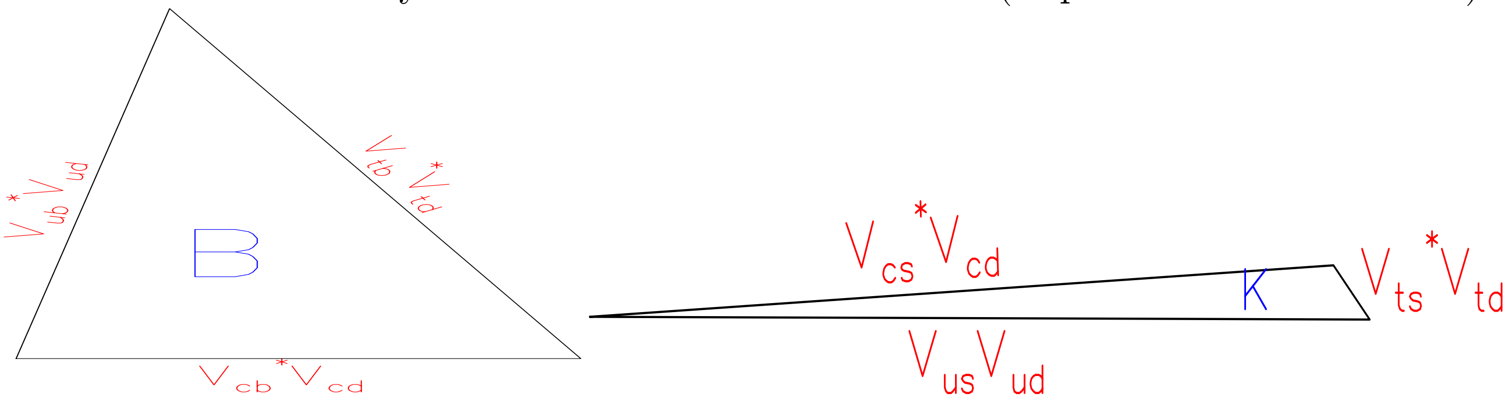


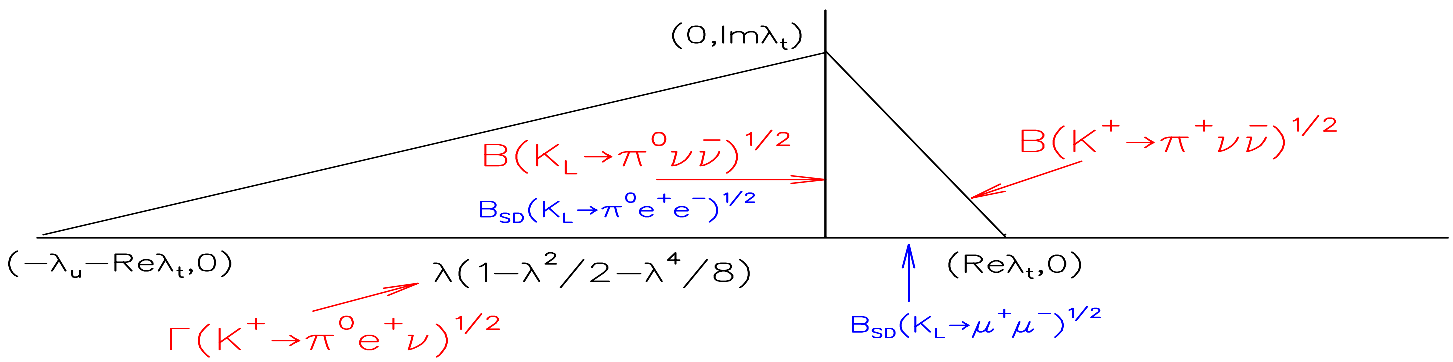



# Rare Kaon Decays and the CKM Matrix

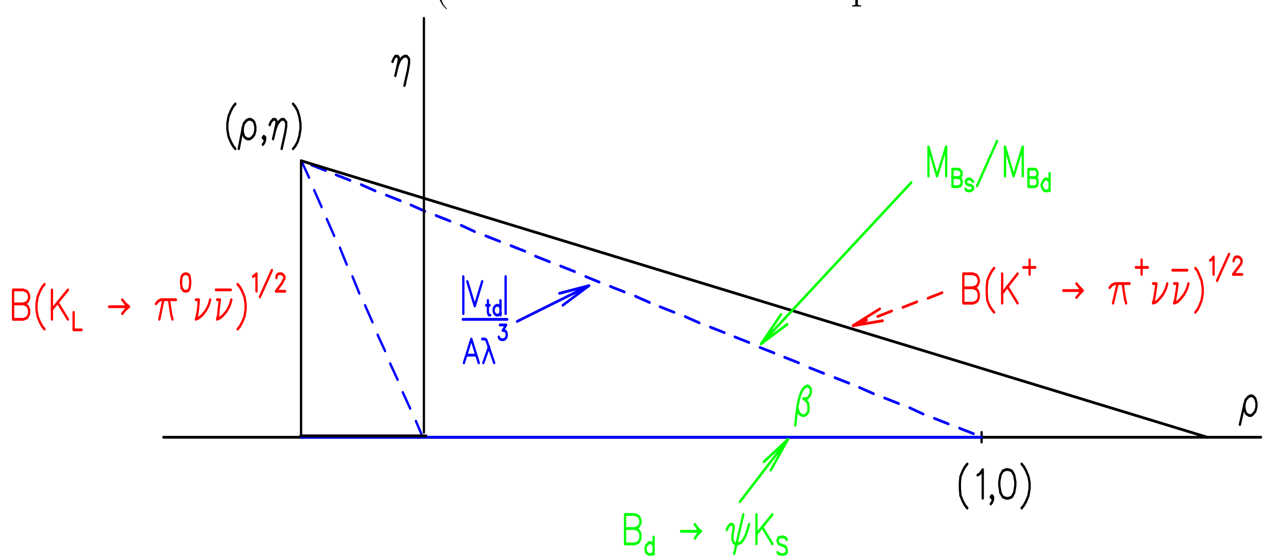
There are six unitarity relations: all should be tested (requires 3 measurements).



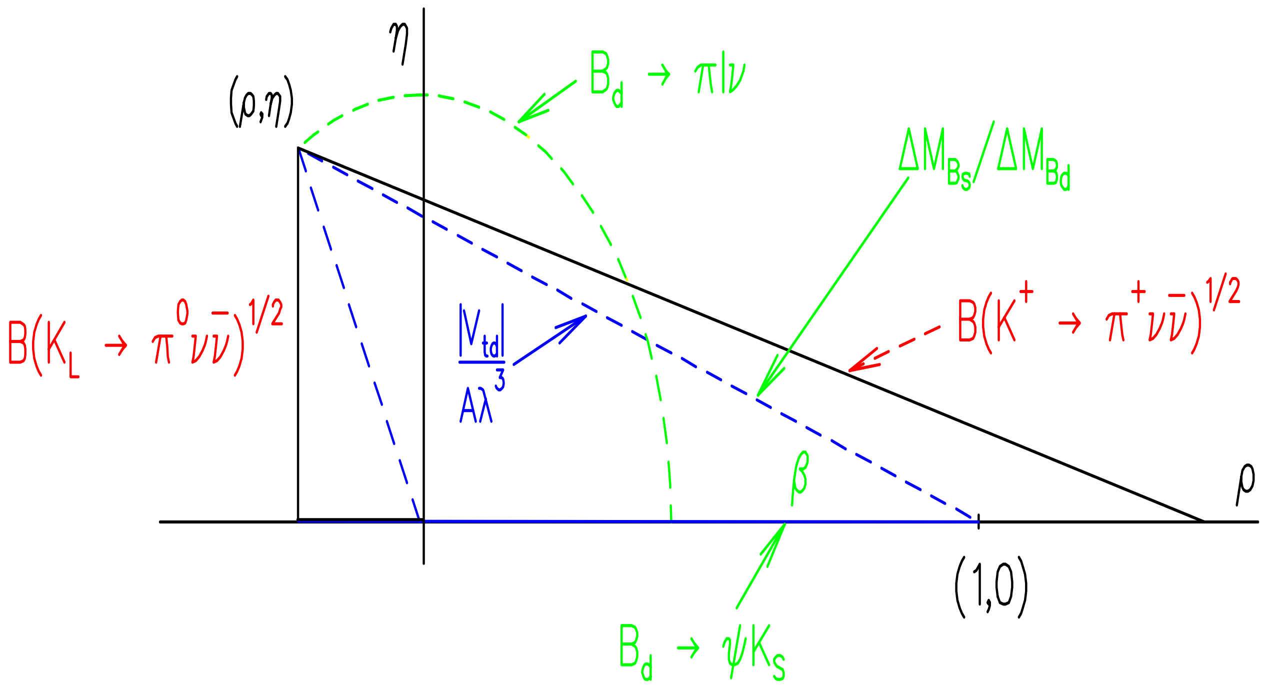

The fundamental measure of CP violation, $J_{CP}$ is related to the area of the triangle and should be measured as well as possible (in as many ways as possible). In the kaon triangle, only two measurements are needed to determine the area: $K^+ \to \pi^\circ e^+ \nu_e$ and $K_L^\circ \to \pi^\circ \nu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



# $K \to \pi\nu\overline{\nu}$




From our current knowledge of the CKM parameters we obtain

## $K^+ \to \pi^+\nu\overline{\nu}$ :

$$\begin{aligned} B(K^+ \to \pi^+\nu\overline{\nu}) &= \frac{\kappa_+\alpha^2 B(K^+ \to \pi^\circ e^+\nu_e)}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \sum_l |X_t V_{ts}^* V_{td} + X_c V_{cs}^* V_{cd}|^2 \\ &= 8.88 \times 10^{-11} A^4[(\overline{\rho}_0 - \overline{\rho})^2 + (\sigma\overline{\eta})^2] \\ &= (0.82 \pm 0.32) \times 10^{-10} \end{aligned}$$

There is also a relation, free of theoretical ambiguity, between $\frac{\Delta M_{B_s}}{\Delta M_{B_d}}$ and $K^+ \to \pi^+\nu\overline{\nu}$ :

$\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu}) < 0.4 \times 10^{-10} \left[P_{charm} + A^2 X(x_t)\frac{r_{sd}}{\lambda}\sqrt{\frac{\Delta M_d}{\Delta M_s}}\right]^2$ with $r_{sd} = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} < 1.4$

$\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu}) < 1.67 \times 10^{-10}$

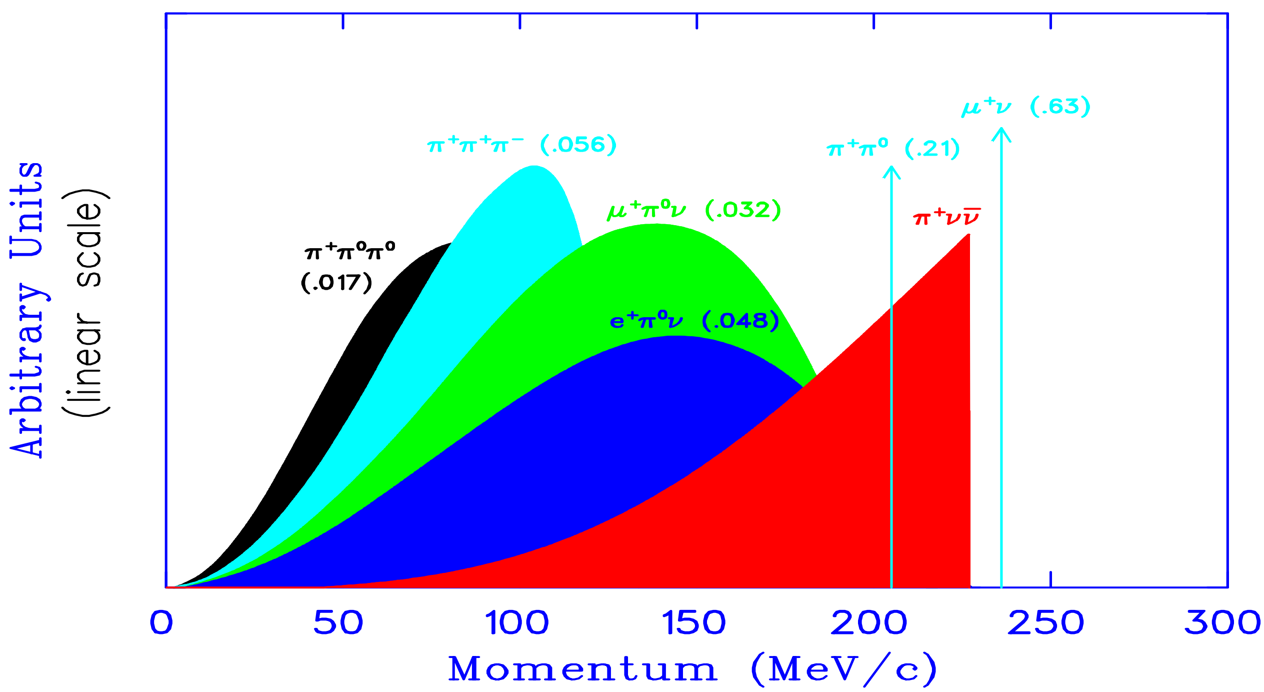
## $K_L^\circ \to \pi^\circ\nu\overline{\nu}$ :

$$\begin{aligned} B(K_L^\circ \to \pi^\circ\nu\overline{\nu}) &= \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\kappa_L\alpha^2 B(K_{e3})}{2\pi^2 sin^4\theta_W |V_{us}|^2} \sum_l |Im(V_{ts}^* V_{td}) X_t|^2 \\ &= 4.08 \times 10^{-10} A^4\eta^2 = 1.56 \times 10^{-4}[Im(V_{ts}^* V_{td})]^2 \\ &= (3.1 \pm 1.1) \times 10^{-11} \end{aligned}$$

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

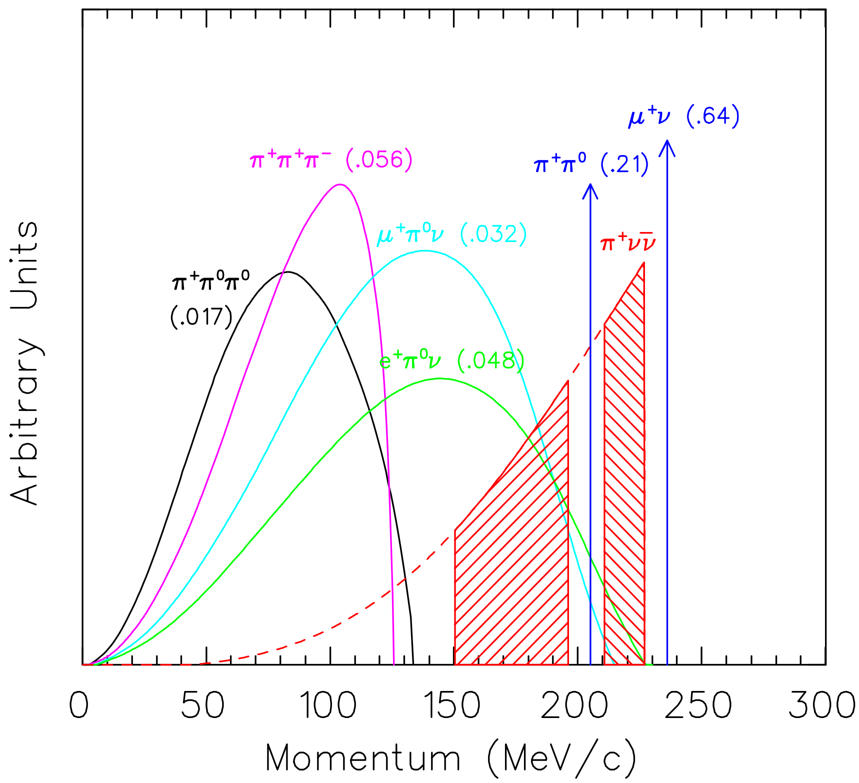
## Measure everything possible

- Positively identify $\pi^+$.
- 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.

<u>E787 strategy</u>



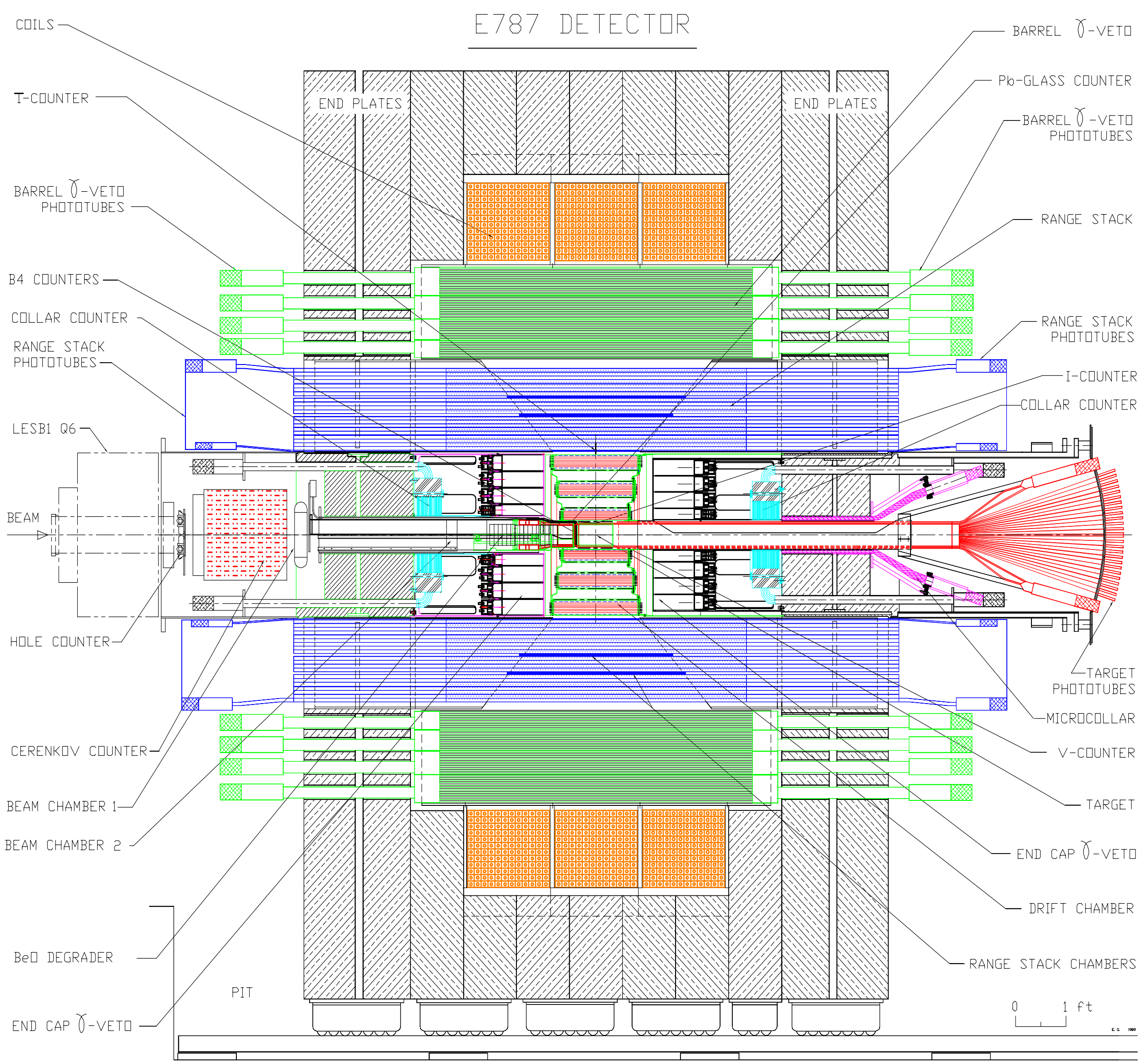

- Work in kaon rest frame $\Rightarrow$ stopped kaon beam
- Search in the high-momentum region ($p_\pi > 211$ MeV/c)
- Stop the decay pion in scintillator
  - Redundant measures of track kinematics: P, E and R
  - $\pi/\mu$ separation
    - Observe $\pi^+ \to \mu^+ \to e^+$ decay sequence $\Rightarrow$ high-speed digitizers (2ns samples, $\sim 7$ $\mu$s depth)
    - dE/dx separation in scintillator
- $\pi$ momentum measurement $\Rightarrow$ low-mass tracking
  - Chamber resolution: $\Delta P/P \sim 0.9\%$ at 205 MeV/c
  - $\sim 1.2\%$ overall resolution

- Photon veto
  - $4\pi$ coverage, typically 15$X_0$
  - Time windows ∼2-3 ns; energy thresholds ∼0.2–3 MeV
  - CsI, Pb-scint, Pb glass
- Beam instrumentation
  - $\mathrm{K}/\pi$ separation
    - Cerenkov counter, lucite radiator
    - Scintillator hodoscopes (dE/dx)
  - Fine spatial segmentation, tracking, good timing
    - Scintillating fiber (5mm square fiber) kaon stopping target
    - MWPC's (1.27 mm wire spacing)
- Rate capability
  - $\sim 5$ MHz of incoming $\mathrm{K}^+$
  - 500 MHz digitizers in barrel, endcap, target, beam hodoscopes
- Minimize inactive material (undetected energy loss)

# E787

# Search for $K^+ \to \pi^+ \nu \overline{\nu}$

Alberta/BNL/Fukui/KEK-Tanashi/KEK-Tsukuba/Osaka/Princeton/TRIUMF



# e787

S. Adler, M.S. Atiya, I-H. Chiang, M. Diwan, J.S. Frank, J.S. Haggerty, V. Jain, S.H. Kettell, T.F. Kycia, K.K. Li, L.S. Littenberg, C. Ng, G. Redlinger, A. Sambamurti, A.J. Stevens, R.C. Strand, and C.H. Witzig

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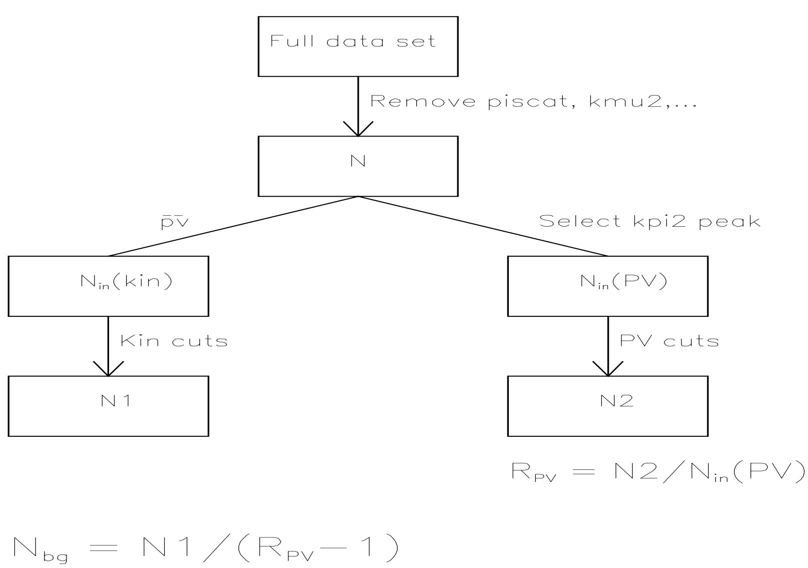
# E787 Summary

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

- Detector and Beam upgrade in 1992–3.
- Engineering run in 1994.
- 1995 — first physics run (PRL **79**, 2204, 1997)
  - 23 week run with 17 weeks of $K^+ \to \pi^+ \nu \overline{\nu}$ data
  - sensitivity = $4.2 \times 10^{-10}$ (background level = $3 \times 10^{-11}$)
- 1996 — shorter run.
  - 16 week run with 13 weeks of $K^+ \to \pi^+ \nu \overline{\nu}$ data
  - increased trigger efficiency, improved acceptance at lower momentum
- 1997 — very short run.
  - 9 week run with 8 weeks of $K^+ \to \pi^+ \nu \overline{\nu}$ data
  - lower momentum, reduced deadtime
  - Analysis of 1995–7 data virtually complete.
- 1995–97 — (PRL **84**, 3768, 2000)
- 1998 — combine FY98 and FY99 into one good final run.
  - 26 week run with $\sim$22 weeks of $K^+ \to \pi^+ \nu \overline{\nu}$ data
  - higher duty factor, long and efficient run, not as long as hoped and not as many protons as hoped
  - Analysis should finish in 2000.

# Offline analysis overview

- Blind analysis
  - Signal region is hidden (by inverting cuts) while cuts are developed and background levels estimated
  - In addition, blind analysis for background estimation.
    - Eliminate low statistics bias.
    - A fraction ($\sim 1/3$) of the data is used to set the cuts; actual cut performance is measured on the remaining data.
- "Bifurcated" analysis
  - A priori identification of background sources
  - Same dataset for background studies and signal search
  - Two independent cuts with high rejection for each background
  - Measurement of background in the signal region at $\mathcal{O}(10^{-3}$–$10^{-2})$ events
- Correlation studies
- Prediction of background levels around signal region (with confirmation)
- Background likelihood analysis (using predetermined likelihood functions) in the signal region for assessing candidate events.



# Offline analysis of 1995-7 dataset

Goals:

- Increase rejection by about a factor of 3 to maintain same bkg level as 1995 analysis for the 95-7 dataset.
- Maintain (or possibly even increase) acceptance at the same time
- Devise methods to increase bkg samples (beyond the obvious increase from increased exposure)
- Further test our understanding of the backgrounds

Analysis chronology

- Cuts and analysis improvements were developed on 1/3 of the 1995 dataset, then tested on 2/3 of 1995 data.
- Calibrations were retuned where necessary on 1/3 1996-7 data. A few cuts were tweaked, based on high statistics. Background measurements from 1/3 96-7 were basically consistent with expectations from 1995. $\Rightarrow$ completely unbiased measurement of bkg levels in 96-7 data up to this point.
- Bkg survivors from 1/3 96-97 examined. Some new cuts devised to gain rejection.
- Final 96-97 bkg level estimated from measurements on 2/3 96-97 data.

# Analysis improvements

$K_{\pi 2}$

- Tracking improvements in range stack and target $\Rightarrow$ better range resolution (core) and smaller tail

$K_{\mu 2}$

- Tracking improvements in drift chamber and better tracking quality cuts $\Rightarrow$ smaller momentum tail
- Range stack dE/dx likelihood analysis $\Rightarrow$ effective against muons downshifting in energy and range
- Improved algorithm for finding the electron from $\mu^+ \rightarrow e^+$ decay $\Rightarrow$ 17% gain in acceptance
- Better optimization of TD likelihood functions
- Better understanding of different sources of TD bkg in $K^+ \rightarrow \mu^+ \nu_\mu$ peak compared to $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ and $K^+ \rightarrow \pi^\circ \mu^+ \nu_\mu$ $\Rightarrow$ much higher statistics for estimating TD rejection

Beam bkg

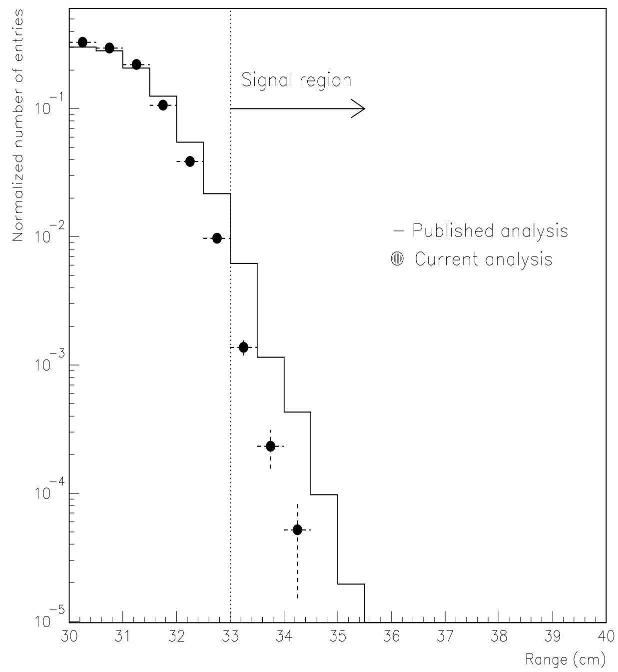
- New cuts against K decay-in-flight.
- Improved cuts in target CCD and K Cerenkov against second track.
- Separation into kaon-entering and pion-entering samples.

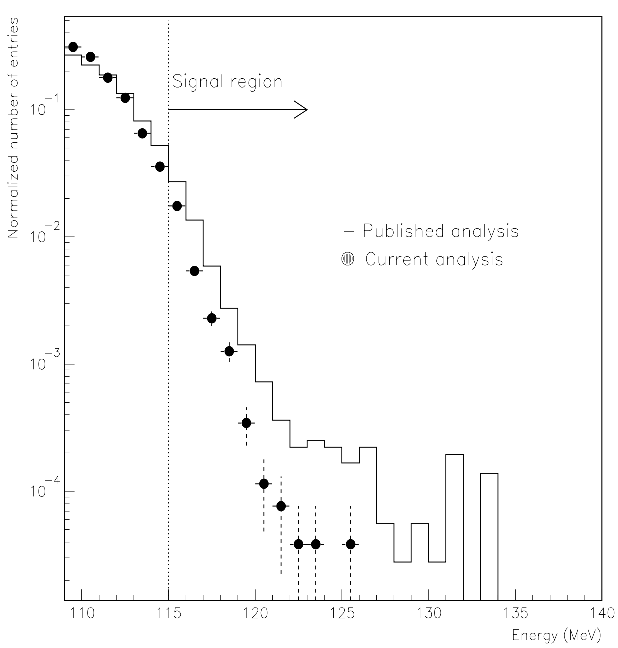
CEX

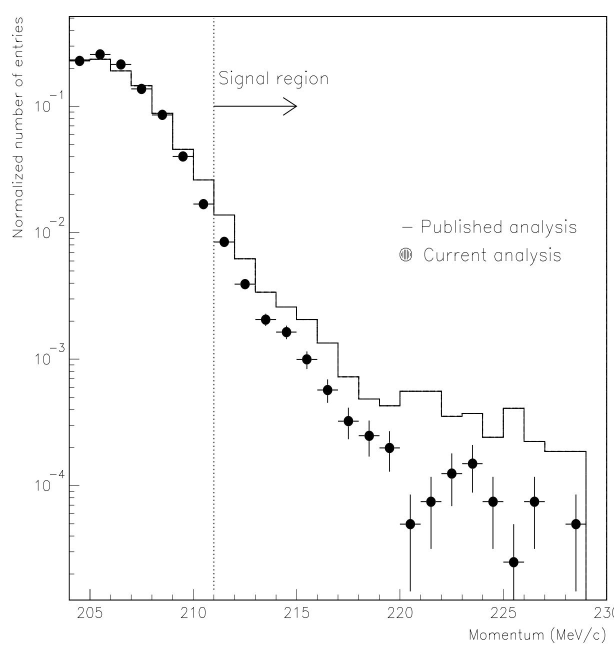
- Benefitted from improved target tracking
- Discriminant function analysis in target and beam hodoscopes

# Improvement in kinematics. (rejection of $K^+ \to \pi^+\pi^\circ$ )

- $\pi^+$ kinematic quantities (range, kinetic energy, & momentum) are used to reject $K_{\pi 2}$ background events.
- Reconstruction improvements have led to a significant increase in rejection.
- Further rejection can be achieved without much loss of acceptance, particularly in the case of the range cut.



## Background

| | 1995 | 1996-7 | Total |
|---|---|---|---|
| $K^+ \to \pi^+\pi^\circ$ | 0.015 | 0.012 | $0.022 \pm 0.005$ |
| $K^+ \to \mu^+\nu_\mu$ | 0.008 | 0.021 | $0.028 \pm 0.010$ |
| 1-beam | 0.0027 | 0.0039 | $0.005 \pm 0.004$ |
| 2-beam | 0.0021 | 0.0047 | $0.016 \pm 0.015$ |
| CEX | 0.0045 | 0.0051 | $0.010 \pm 0.007$ |
| Total | | | $0.08 \pm 0.02$ |

'golden' region #1: $A/A_0 = 0.36$, Bkgd $= 0.010 \pm 0.003$

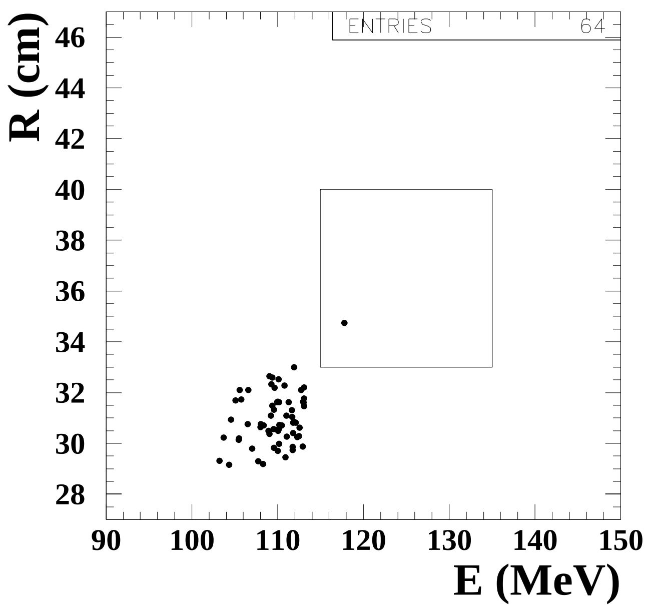
'golden' region #2: $A/A_0 = 0.33$, Bkgd $= 0.006 \pm 0.002$

## Acceptance

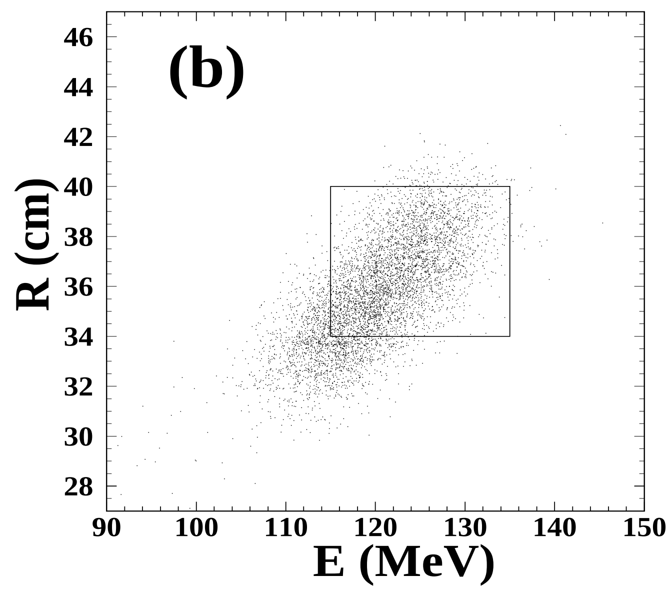
| | 1995-7 |
|---|---|
| $K^+$ stop efficiency | $0.704 \pm 0.004^{stat} \pm 0.009^{syst}$ |
| $K^+$ decay after 2 ns | $0.850 \pm 0.001$ |
| $K^+ \to \pi^+\nu\overline{\nu}$ phase space | $0.155 \pm 0.001^{stat} \pm 0.001^{syst}$ |
| Solid angle acceptance | $0.407 \pm 0.001$ |
| $\pi^+$ nucl. int., decay-in-flight | $0.513 \pm 0.005^{stat}$ |
| Reconstruction efficiency | $0.959 \pm 0.001$ |
| Other kinematic constraints | $0.665 \pm 0.007^{stat} \pm 0.020^{syst}$ |
| $\pi - \mu - e$ decay acceptance | $0.306 \pm 0.005^{stat} \pm 0.004^{syst}$ |
| Beam and target analysis | $0.699 \pm 0.001$ |
| Accidental loss | $0.785 \pm 0.002$ |
| Total acceptance | $[0.208 \pm 0.005^{stat} \pm 0.021^{syst}]$% |

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

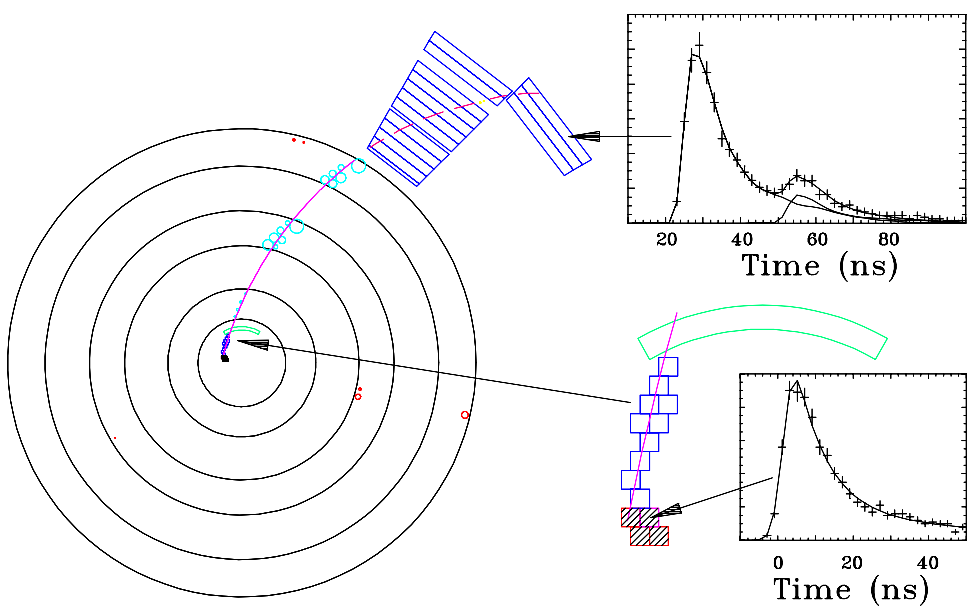
## 1995–97 Data




## Monte Carlo




## Event Display

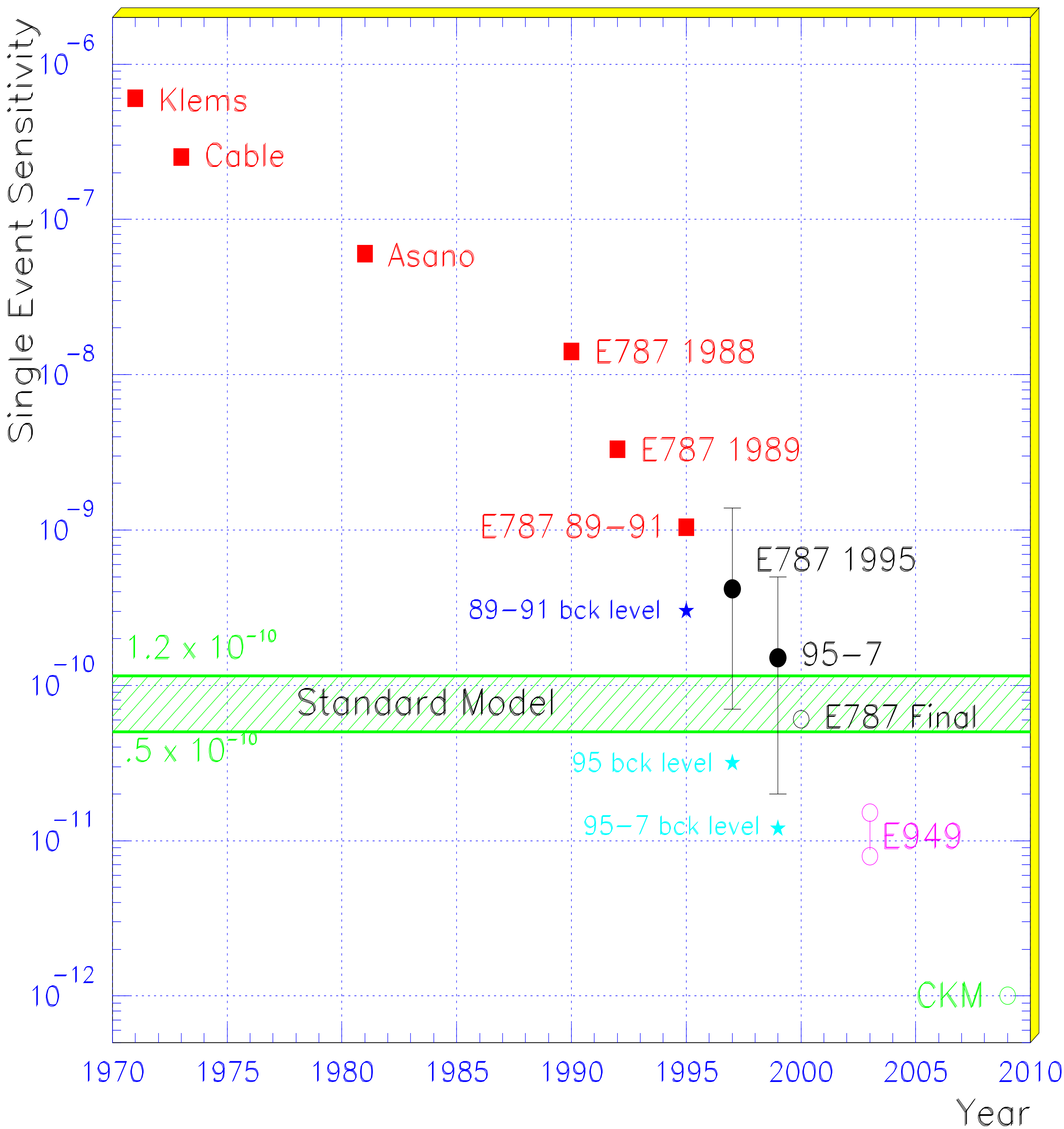



$$\mathbf{BR}(K^+ \to \pi^+ \nu \overline{\nu}\ ) = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$

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

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

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

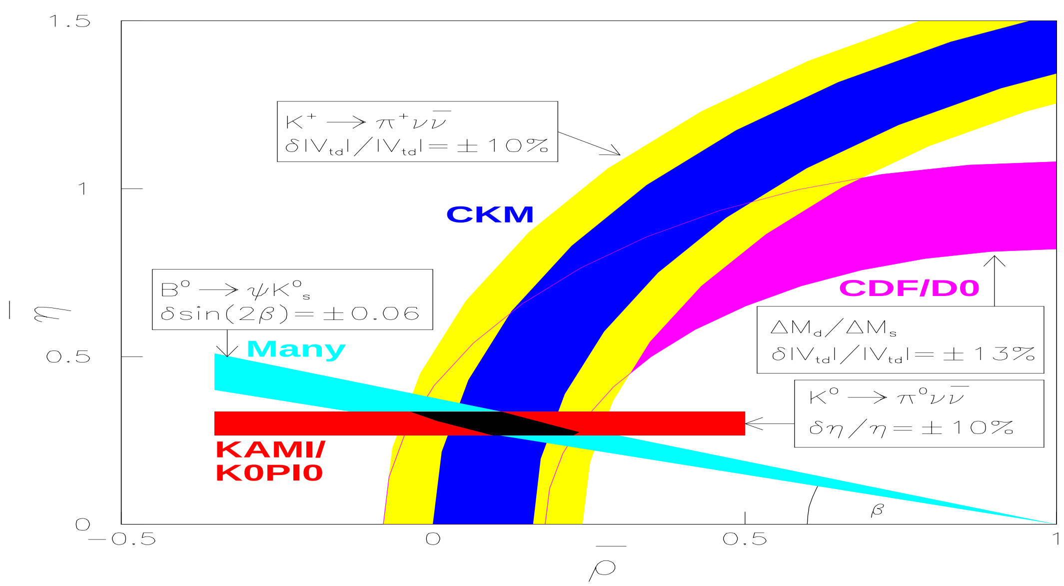


# Future Kaon contribution to the CKM Matrix

Measurements and tests of the Standard Model:

- Determine $Im(\lambda_t)$ and $J_{CP}$ to 7–8% (now 22% and ~40%)
- Overconstrain the angle $\beta$ 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 $K^+ \to \pi^+ \nu\overline{\nu}$

Future contraints on $\overline{\rho}$ and $\overline{\eta}$




Expressed in terms of $\lambda_t$: