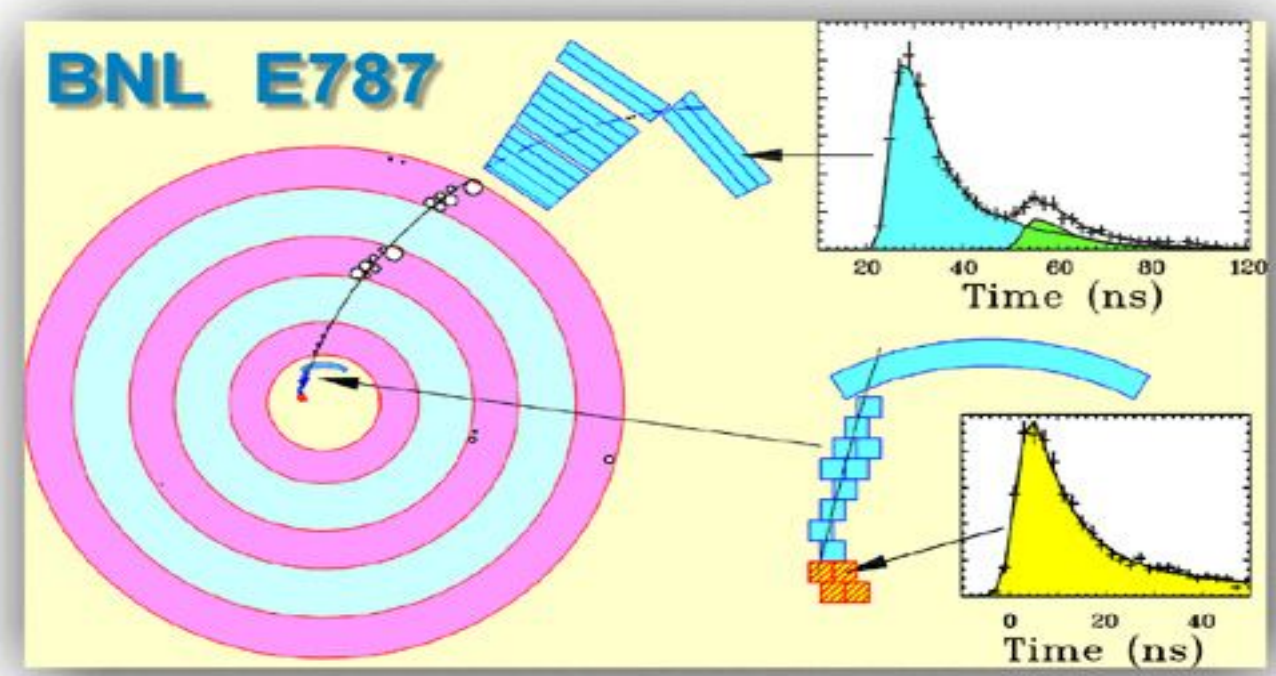
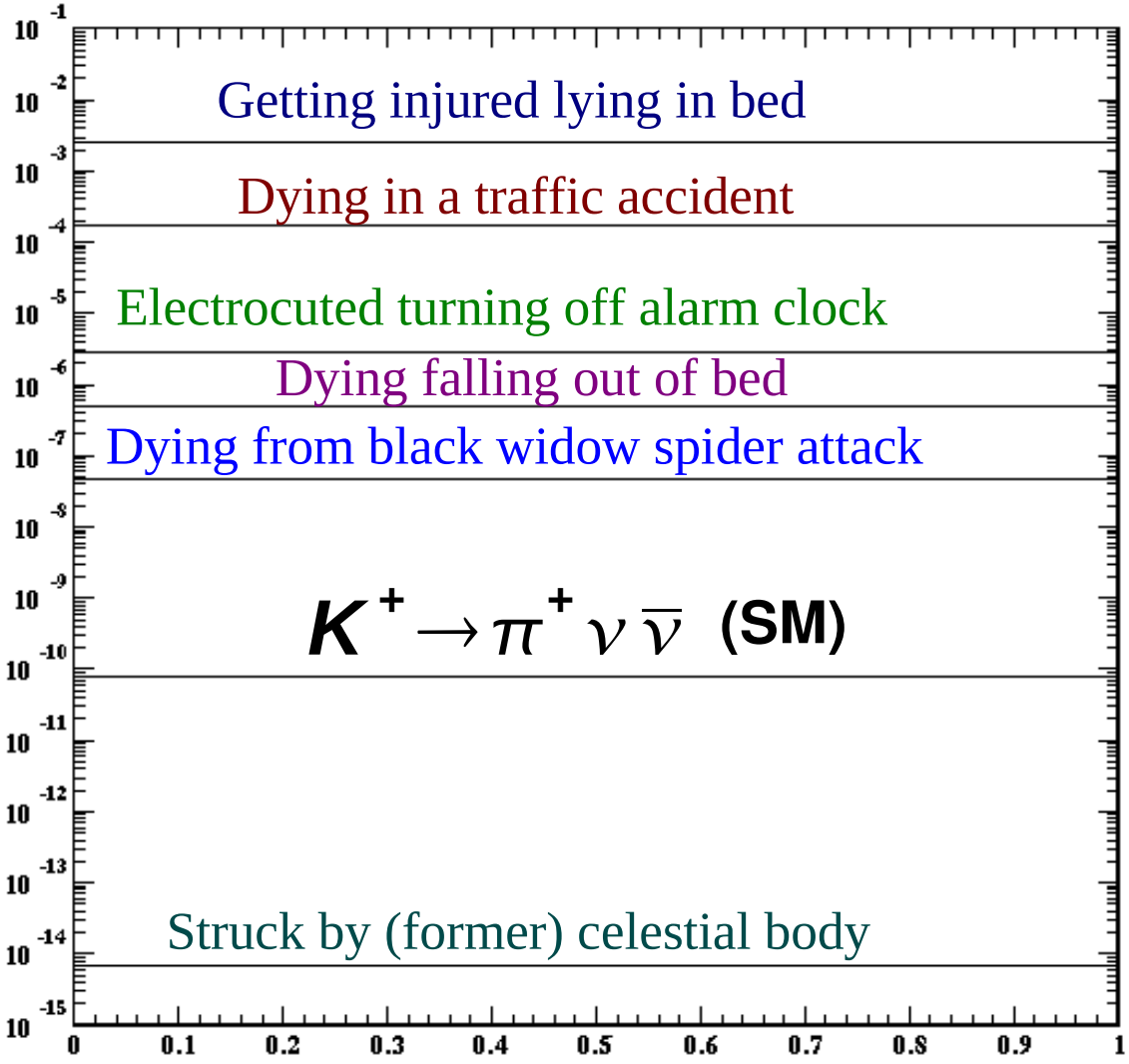
The Experiment E787/E949 at AGS



The Experiment, where Physicists observed one of Rareest decay in the Nature.

Annual Risk (L . Laudan, The Book of Risks)



Why the search for the Rare Decay

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

> **To measure the probability of this decay to occur, which is predicted very precisely in the theory (SM) . Any inconsistency will be an indication of new physics or some loopholes in the way we claim to understand the Universe.**

> *To understand the matter – antimatter asymmetry in the Unive*
The Universe is dominated by matter, rather than antimatter when they were probably equally common in the earliest stag the Universe. Why is antimatter so uncommon today?

> Is CP violation the answer to this matter-antimatter assy-mmetry in the Universe?

> **Does the measurement of the probability of this rare decay sheds light on the amount of CP violation ? The answer is "YES".**

Standard Model and Golden Modes.

- The weak eigenstates are connected to the mass eigenstates via the CKM matrix as:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{ckm} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

Unitary Matrix

In terms of Wolfenstein Parametrization

With $\lambda = 0.22$

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

A non-vanishing value of η is responsible for CP violation in the Standard Model.

Nature Provides Only few golden Modes..

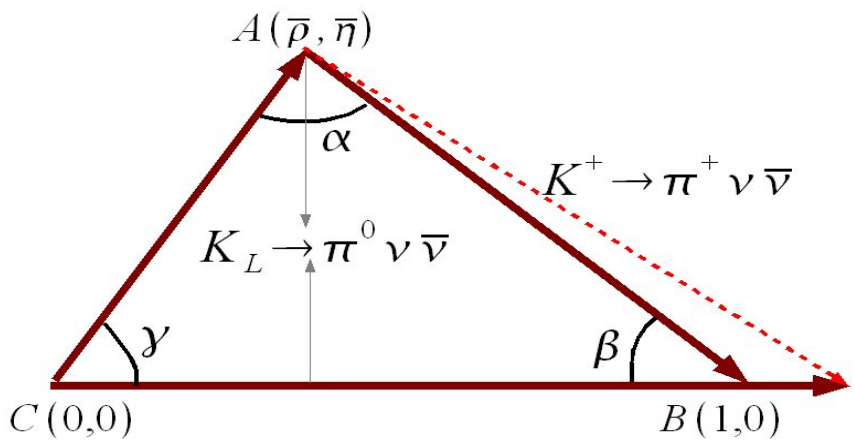
- Modes with little theoretical uncertainty that can be used to extract the fundamentel parameters in the CKM Matrix.

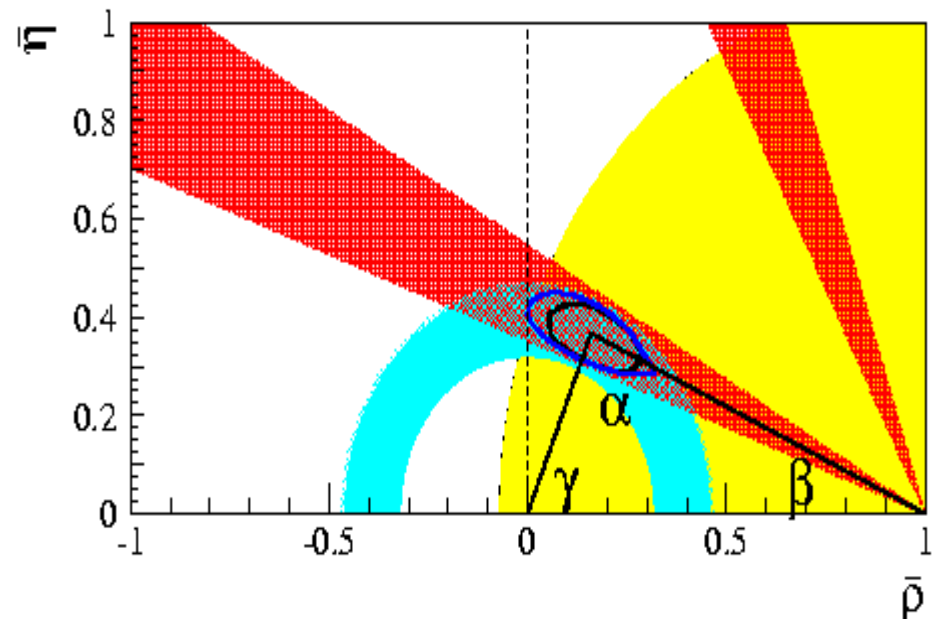
$$K^+ \to \pi^+ \nu \bar{\nu} \;\; - \;\; |V_{ts}^* V_{td}|$$

$$K_L^0 \to \pi^0 \nu \bar{\nu} \;\; - \;\; \mathrm{Im}(V_{ts}^* V_{td})$$

$$B \to J/\psi K_s \;\; - \;\; \beta$$

$$\Delta M_d / \Delta M_s \;\; - \;\; |V_{td}| / |V_{ts}|$$



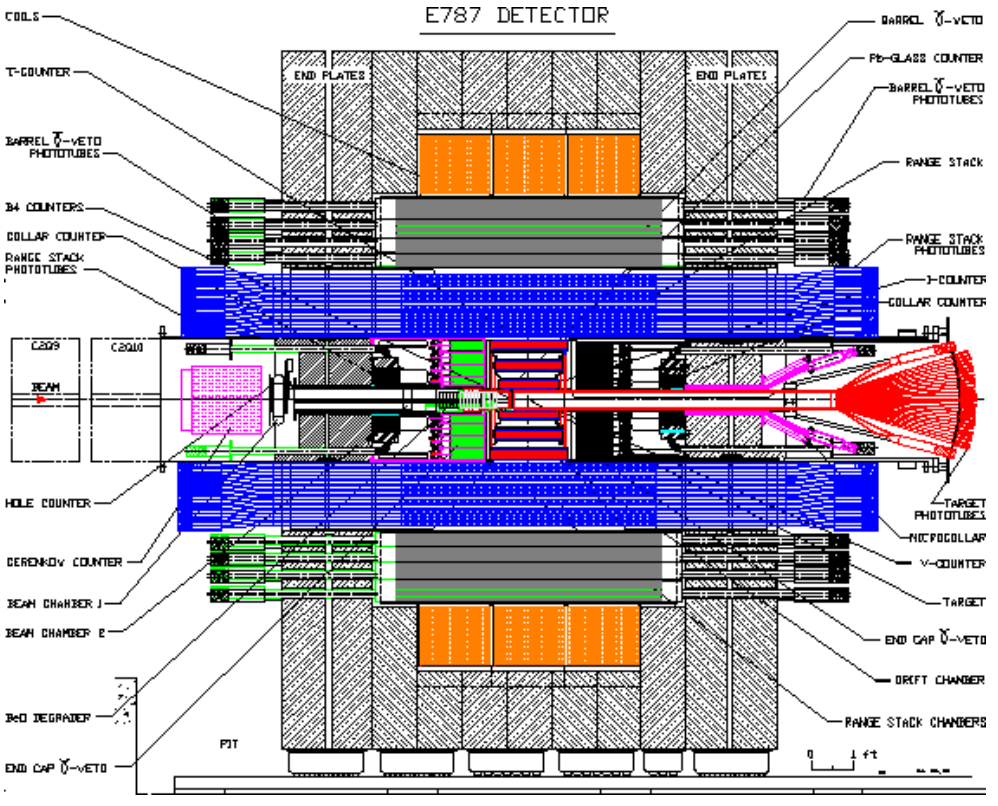


***hep – ph* / 0210291, *Oct.* 2002**
(A.J. Buras)

E787/ E949 Detector and Technique.

BNL/Fukui Univ /KEK/Princeton/Osaka/TRIUMF/Alberta/FermiLab/INR/IHEP

- *3 m diameter solenoidal detector.*
- *About 700 MeV/c K's made to stop in the 400 element plastic Scintillator fiber target, read out by 500 Mhz GaAs based CCD's.*
- Wait 2 ns for Kaon to decay.
- *Track and momentum measured in Drift Chamber.*
- *π^+ Range, Energy and the decay is followed using*
- Hermetic Photon vetoing *via*



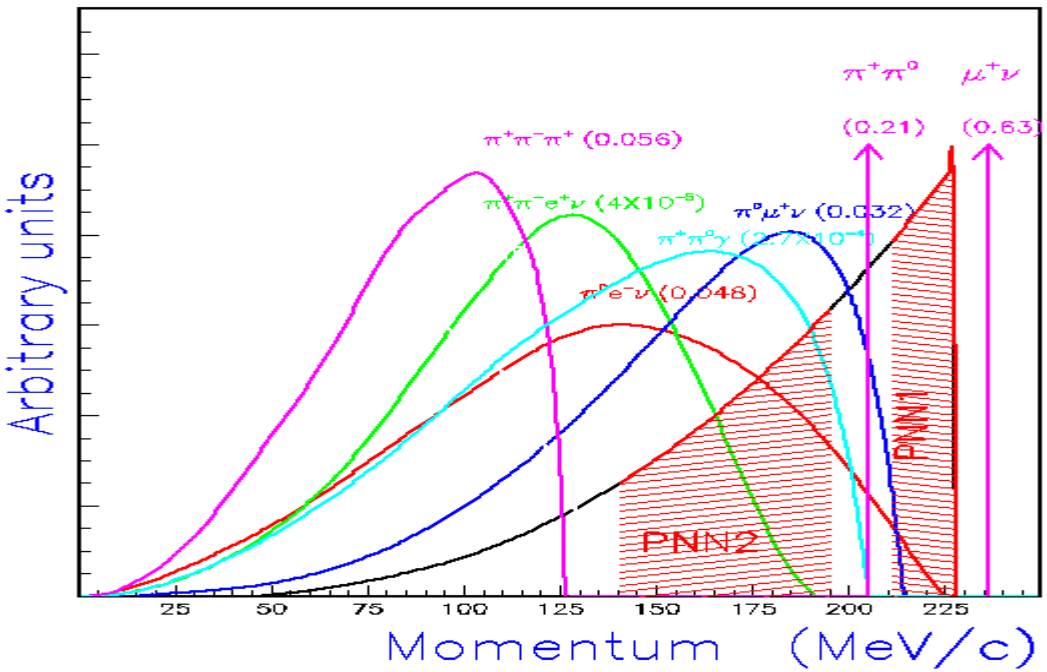
$10^6:1\ \pi^0$ rejection

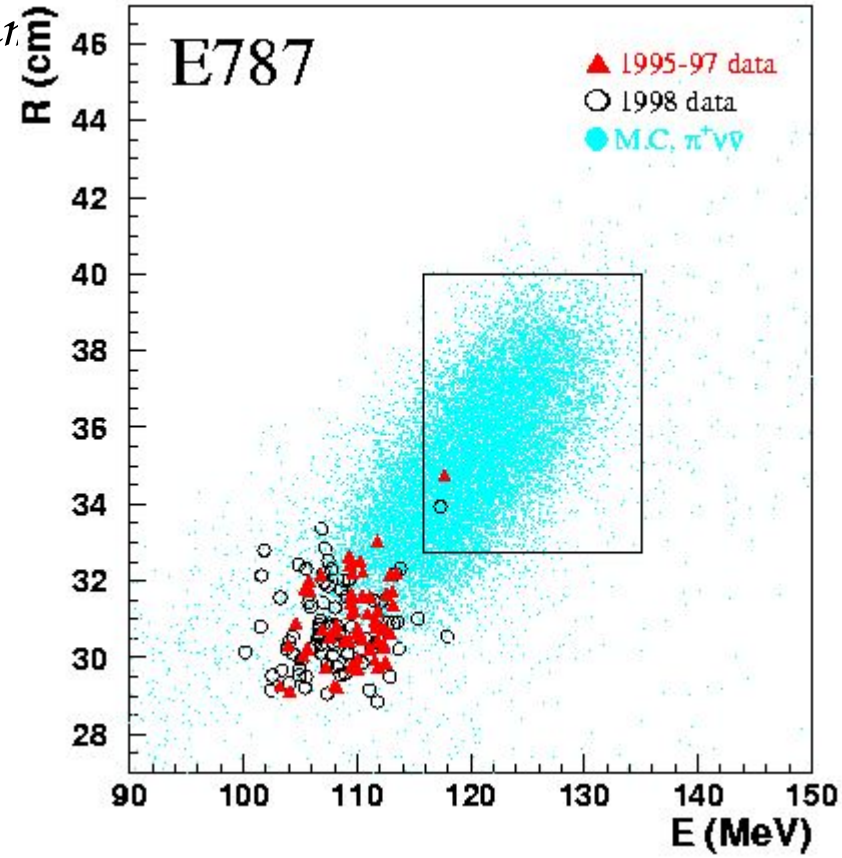
$10^8:1\ \mu^+$ rejection

Evidence for the Decay

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

- *Two events were observed in the pion momentum region* . $P_{\pi^+} > 211\,\text{MeV}$





PRL 88, 041803 (2001)

- Two events consistent with $K^+ \to \pi^+ \nu \bar{\nu}$

$$Br(K^+ \to \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10} \quad [SM: (0.72 \pm 0.21) \times 10^{-10}]$$

Impact on the CKM Matrix.

- *Two observed signal events can be used to put limit on |Vtd|.*

$$0.007 < |V_{td}| < 0.030 \quad (68\%\,\mathrm{C.L.})$$

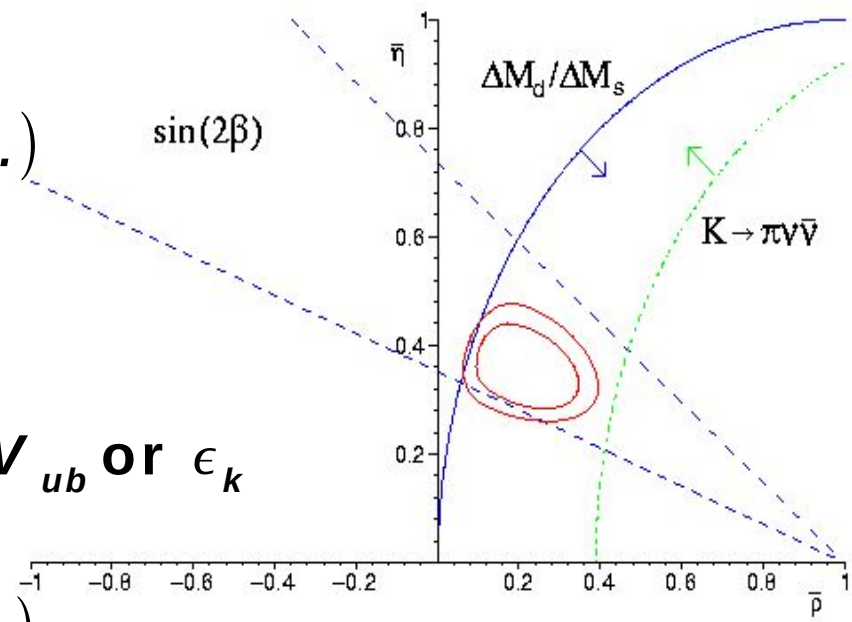
With $\overline{m}_t(m_t) = 166 \pm 5\,GeV/c^2$

$V_{cb} = 0.041 \pm 0.002$

- Does not require knowledge of V_{ub} or ϵ_k

$$0.004 < |V_{td}| < 0.014$$

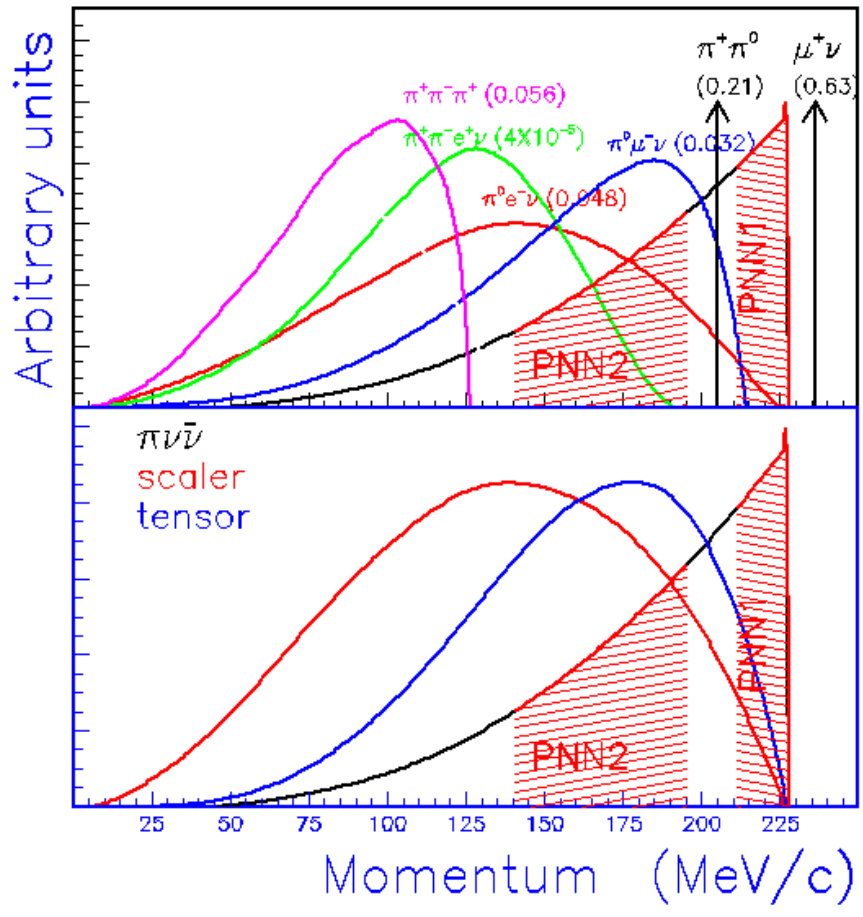
(PDG, July 2002) $(90\%\,C.L.)$



A B -free measurement of these parameters will be an important test of *SM.*

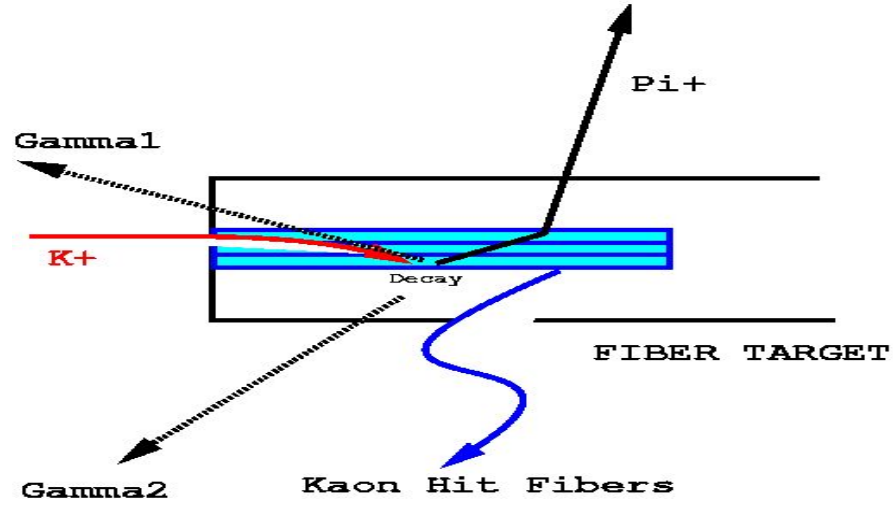
$K^+ \to \pi^+ \nu \bar{\nu}$ At Lower Momentum. (Below the $K^+ \to \pi^+ \pi^0$ Peak)

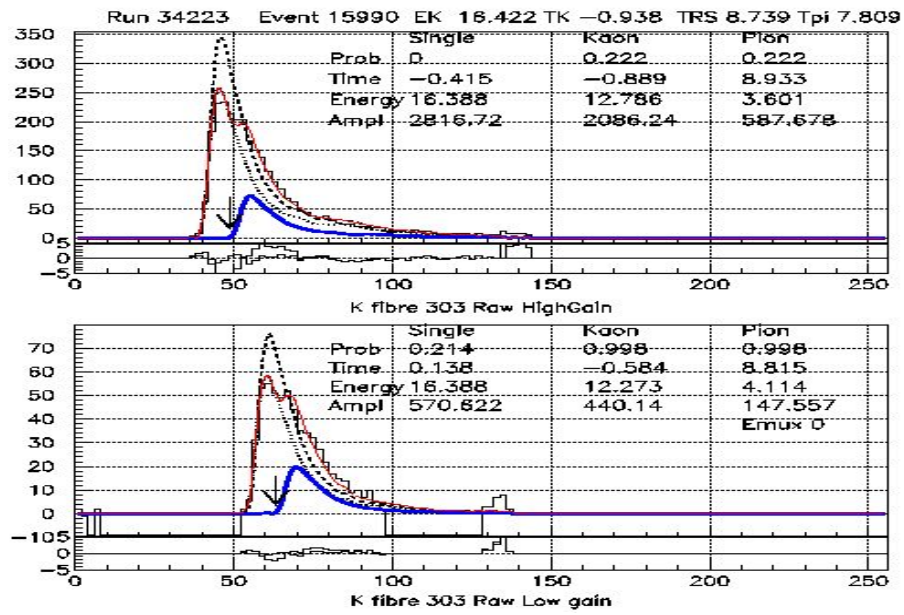
- *Much larger phase space acceptance below the peak.*
- Explore the entire pion spectrum.
- More sensitive to scalar or tensor type interactions.
- Exotic Physics possibilites such as $K^+ \to \pi^+ X^0$ where X^0 has some mass need to be examined.
- Other exotic physics could modify the pion spectrum , e.g. $K^+ \to \pi^+ J J$
- Difficult Backgrounds:
  1) Pion Nuclear interactions in target.
  2) Ke4 Background with π^- and e^+ disappearing in TG by absorption



PNN2 Backgrounds and Tools.

- Large Background from $K^+ \rightarrow \pi^+ \pi^0$ in which the π^+ undergoes nuclear interaction in the scintillator fiber target.
- Photons from π^0 lose the directional correlation with π^+ after π^+ scatters in the target.
- Suppression of this background depends on the efficiency of finding evidence of pion scatter in the target.
- *After reconstruction of pion and kaon, use CCD read out to find pion time pulses hidden under K-fibers.*





Ke4 Background in the PNN2 region

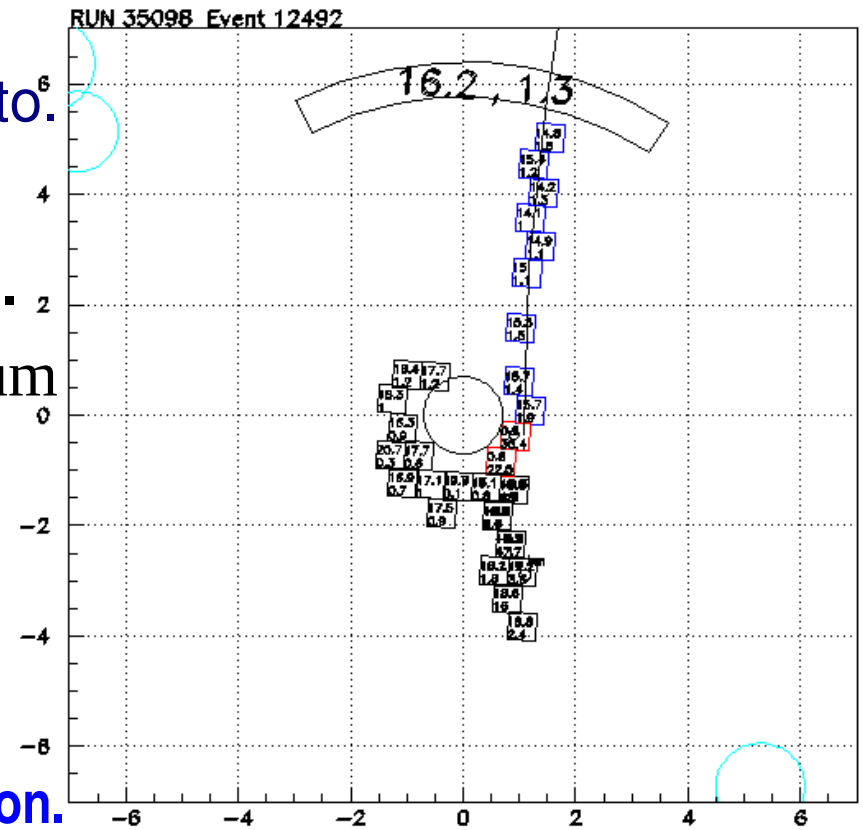
* $Br(K^+ \rightarrow \pi^+ \pi^- e^+ \nu)$: 4×10^{-5}

a) No Photons in the final state to veto.

b) π^- can disappear by absorption.

c) e^+ can disappear by annihilation.

d) π^+ momentum falls in the momentum region 150 to 190 MeV/c.



* Tools:

a) Identify events in data.

b) Find extra energy in the target not belonging to either kaon or positive pion.

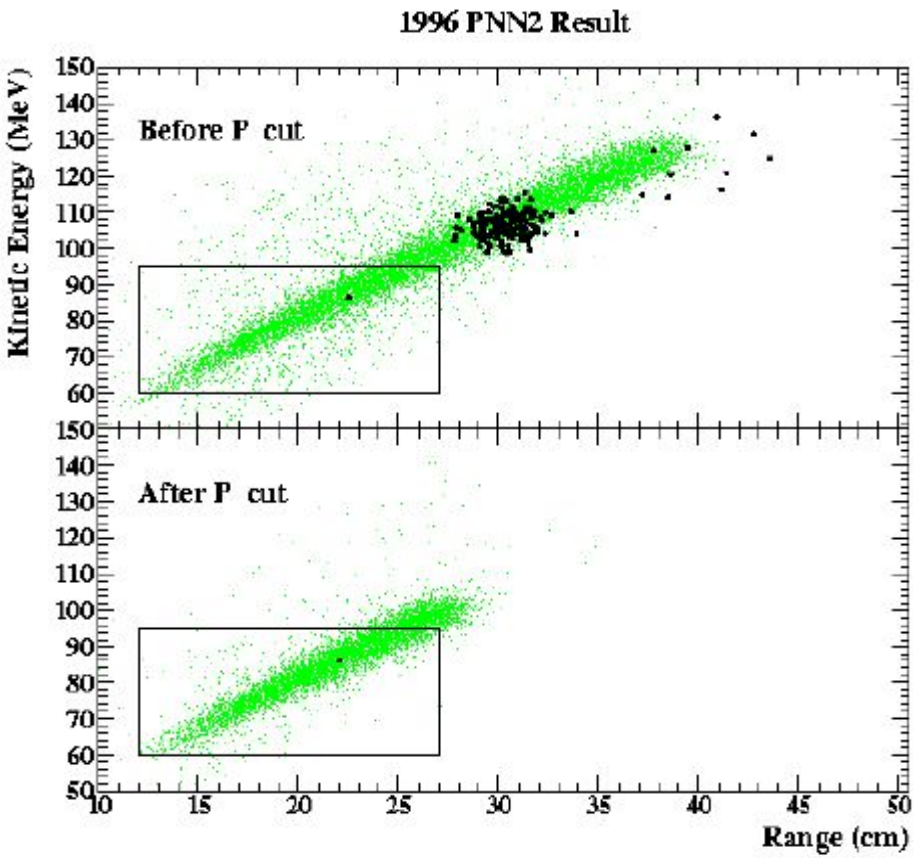
c) Use data and Monte Carlo to measure the Background.

d) Fortunately, the phase space for the decay vanishes as kinetic energy of π^- and e^+ goes to 0.

Results from PNN2 Region

1996: K Stop in TG: 1.12×10^{12}

PL B 537, 211 (2002)

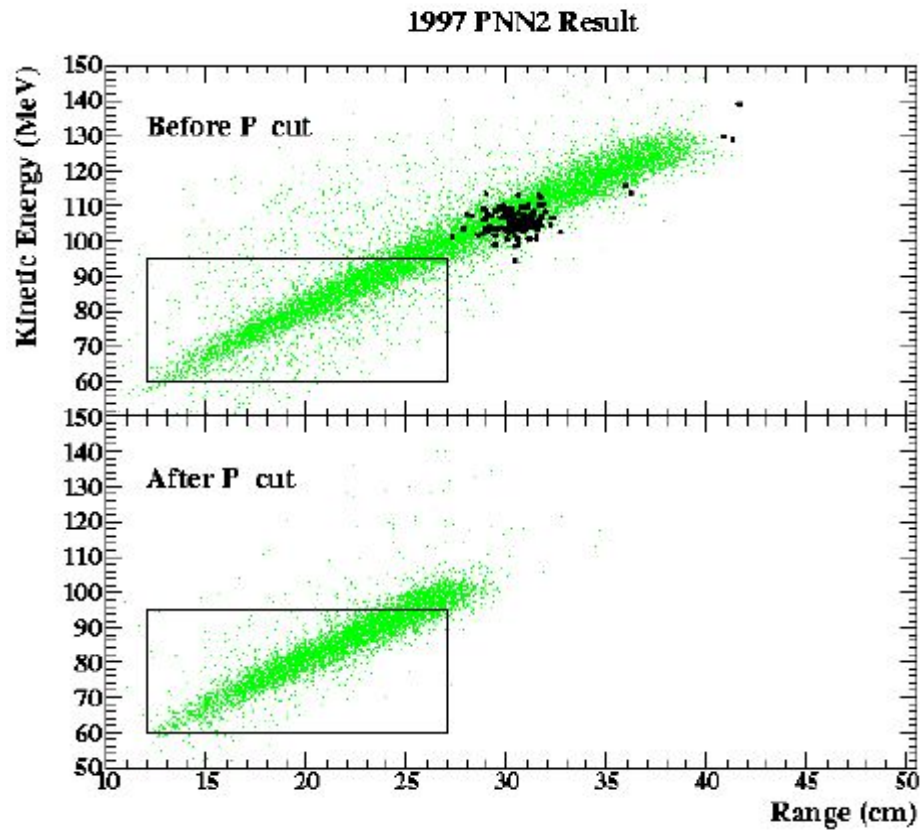


Total Background = 0.73

Total Acceptance = 7.65×10^{-4}

1997: K Stop in TG: 6.08×10^{11}

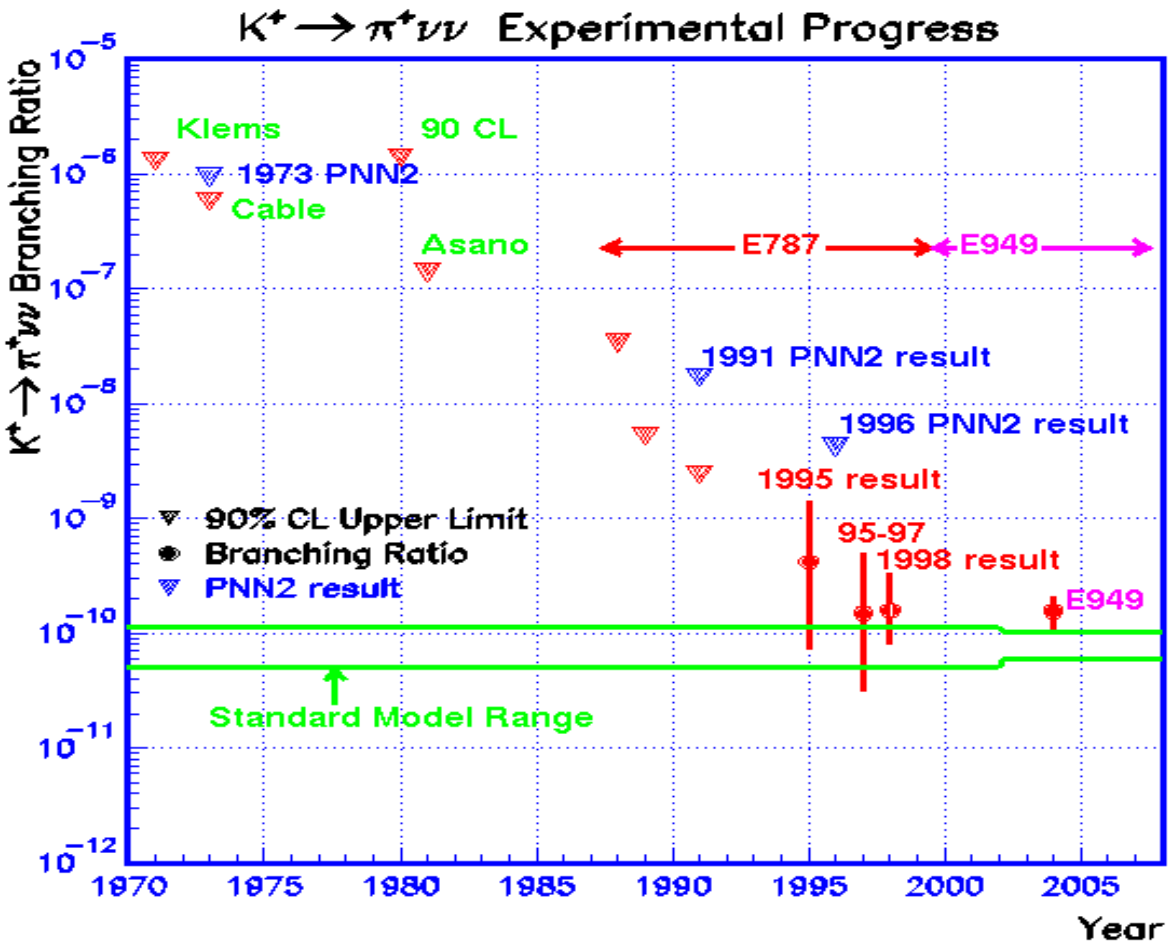
Preliminary



Total Background = 0.48

Total Acceptance = 9.71×10^{-4}

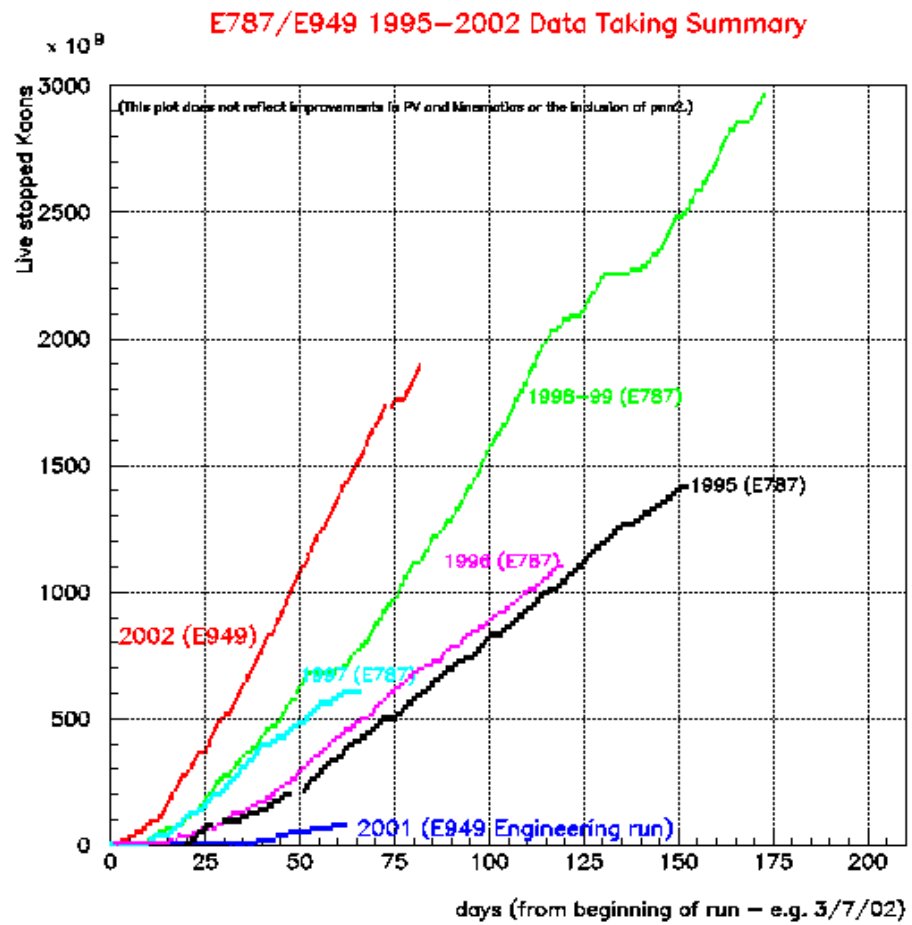
Results from E787 and Progress.



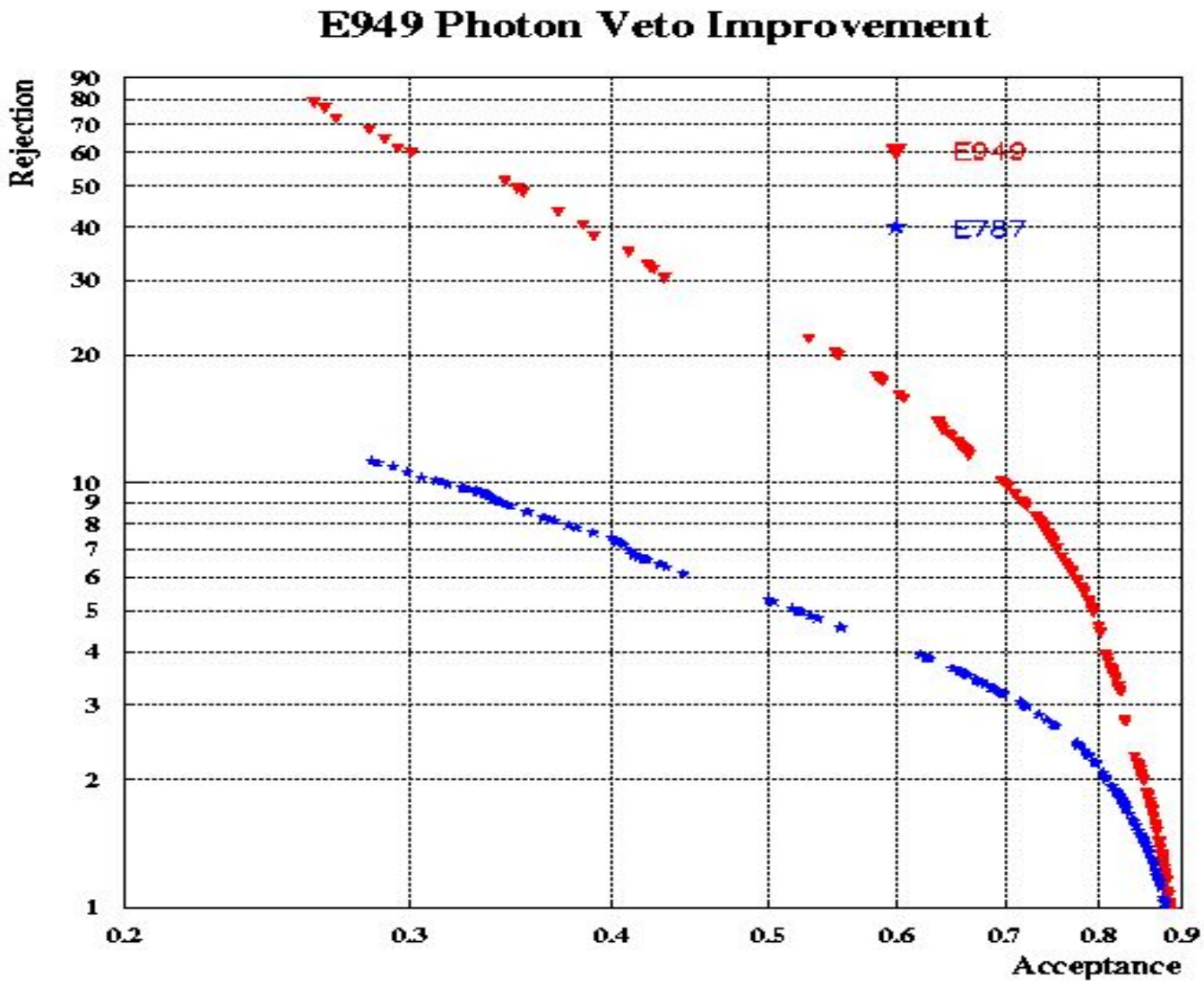
E949 At AGS.

- Solid Projection of sensitivity gain from E787.
- Sensitivity for $Br(K^+ \to \pi^+ \nu \bar{\nu})$ of $(9-16)\times 10^{-12}$

  Observe 5-10 SM events in the running period of 60 weeks
- *Background small (PNN1) and well understood.*
- *Projected to explore any incon-sistency with SM.*
- Measure $|V_{td}|$ *at 20-30% level if* the SM expectation is confirmed.



Improvement in Photon Detectors at E949



Summary

- E787 observed two candidate events for the decay $K^+ \to \pi^+ \nu \bar{\nu}$ above the $K^+ \to \pi^+ \pi^0$ peak with an expected background of 0.15 ± 0.05

$$Br\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

consistent with the SM prediction of $(0.72 \pm 0.21) \times 10^{-10}$

- *Major new efforts is in progress to explore the more of the pion momentum spectrum. The low momentum region is dominated by $K^+ \to \pi^+ \pi^0$ scatter backgrounds. 1996 results published . Results from the 1997 data set is to be published soon.*

- *E949 ran for about 12 weeks in early 2002.Analysis is in progress. Expecting to achieve the sensitivity of E787. Future is uncertain.*

- *With the improved photon detection efficiency at E949, it is expected to achieve the required sensitivity to observe signal events in the lower momentum region also.*