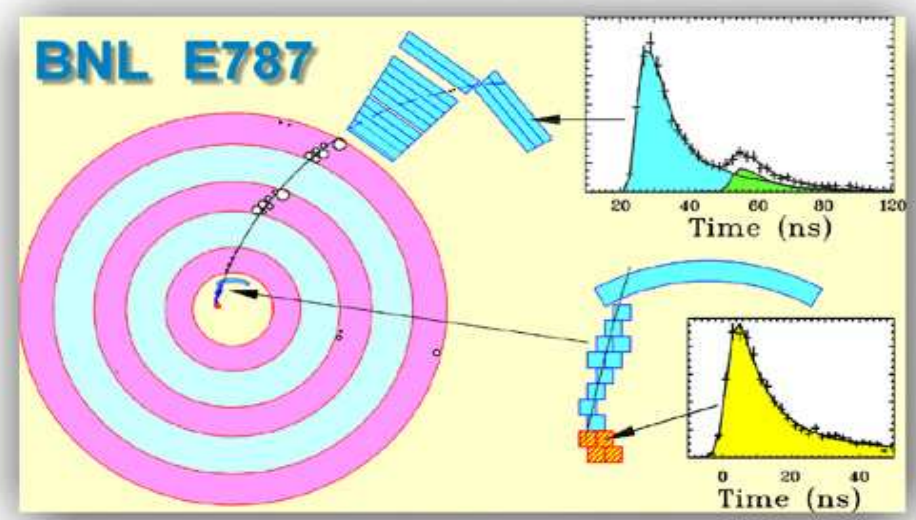


HEP Seminar
KEK, Tsukuba, Japan
Sept. 25, 2003

New Results from BNL-E787 on $K^+ \to \pi^+ \nu \bar{\nu}$ below the $K_{\pi 2}$ peak.

BROOKHAVEN NATIONAL LABORATORY

Bipul Bhuyan

Outline

* **Physics Motivation.**
* Detector and Procedure
* **Analysis and Results from E787.**
* **Status of E949.**
* **Future and Conclusion.**

Search for New Physics.

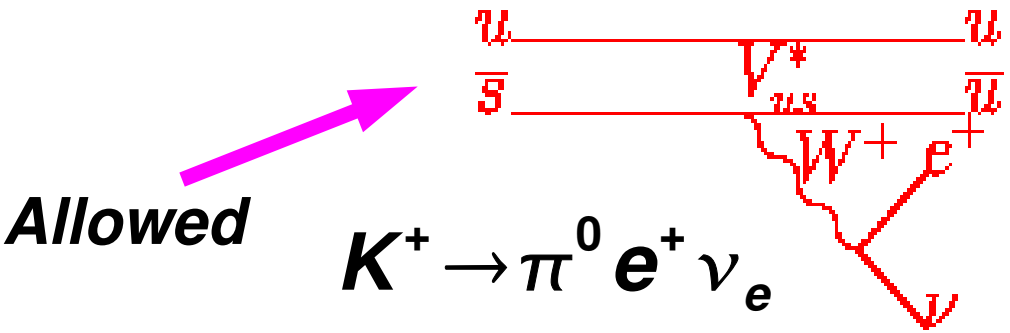
* TWO WAYS:

1) Searches at the kinematic or the high energy limit i.e. Direct Production.

2) Indirect searches in rare decays or with precision measurements i.e. Virtual Production.

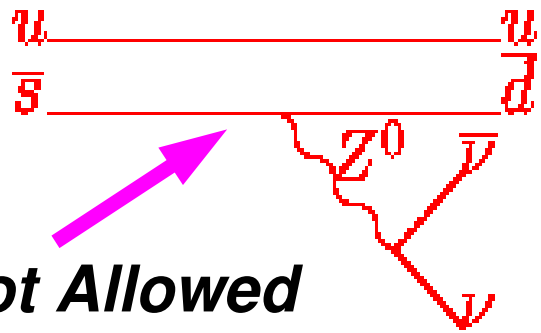
The Decay $K^+ \to \pi^+ \nu \bar{\nu}$ in the Standard Model

* A Flavor Changing Neutral Current process:



Allowed

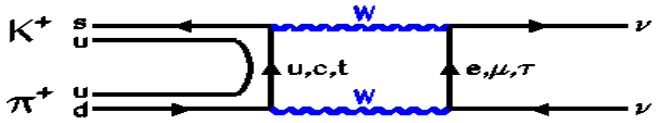
$K^+ \to \pi^0 e^+ \nu_e$

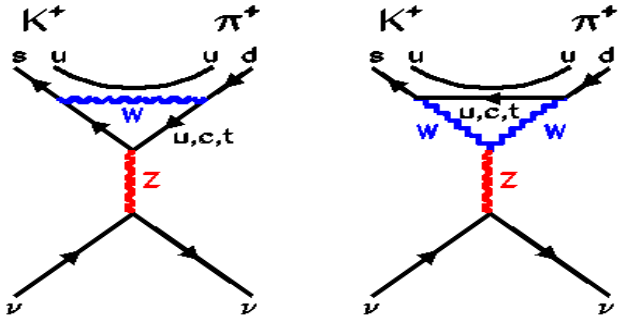


Not Allowed

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

* However...





Can proceed very slowly through these 2-order loop diagram. Because of the breaking of flavor symmetry and the very large violation of quark mass equality by the top quark, leads to its domination for the decay .

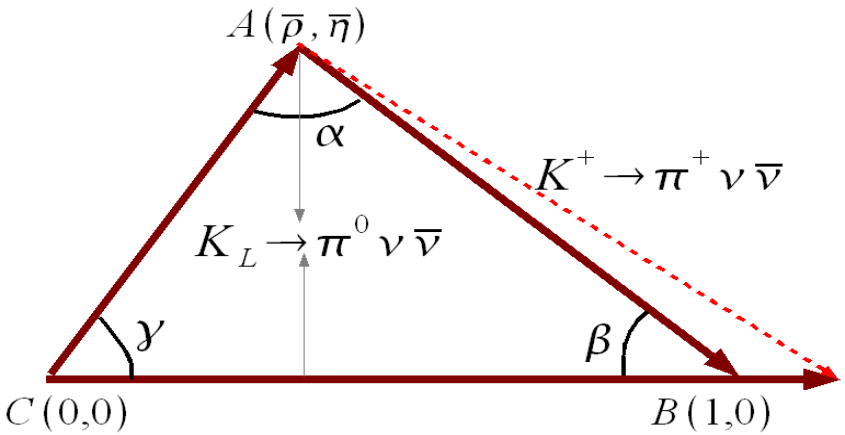
$$B(K^+ \to \pi^+ \nu\bar{\nu}) \alpha |X_t V_{ts}^* V_{td} + X_c V_{cs}^* V_{cd}|^2$$
$$= (0.72 \pm 0.21) \times 10^{-10}$$

(Phys.Lett. B530 (2002) 108-116), hep-ph/0112135

Large error is due to uncertainties in the parameters going into the Equation.

Measure $B(K^+ \to \pi^+ \nu\bar{\nu})$: Measure $\lambda_t = |V_{ts}^* V_{td}|$

A 10% measurement of $B(K^+ \to \pi^+ \nu\bar{\nu})$ will result in a measurement of $|V_{td}|$ at 6-7% level.



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

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

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

Nature Provides Only few golden *Modes..*

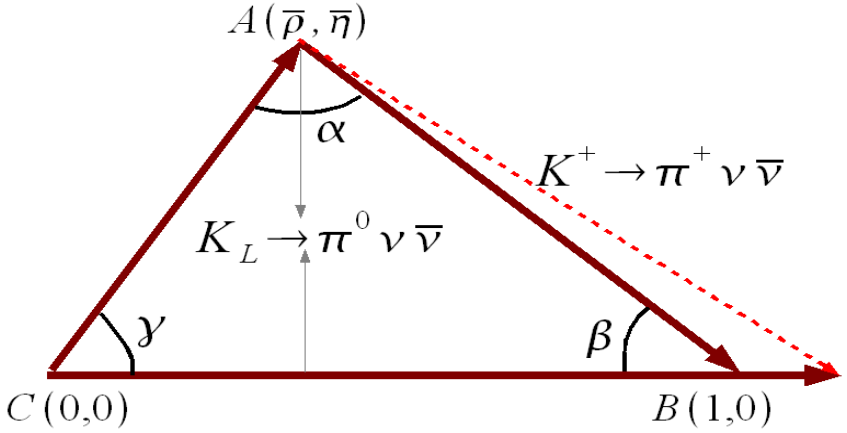
- Modes with little theoretical uncertainty that can be used to extract the fundamentel parameters in the CKM Matrix.

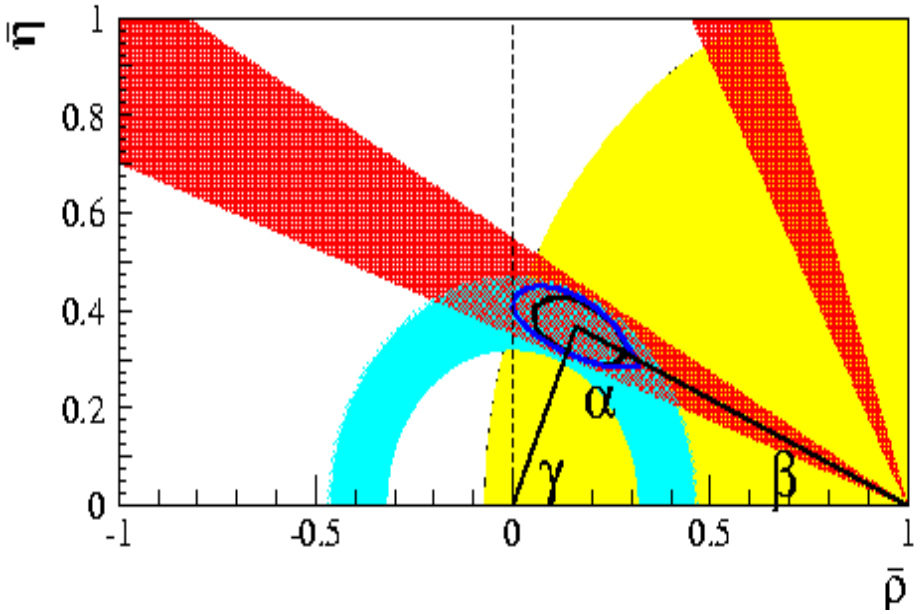
$$K^+ \to \pi^+ \nu \bar{\nu} \quad \Rightarrow \quad |V_{ts}^* V_{td}|$$

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

$$B \to J/\psi K_s \quad \Rightarrow \quad \beta$$

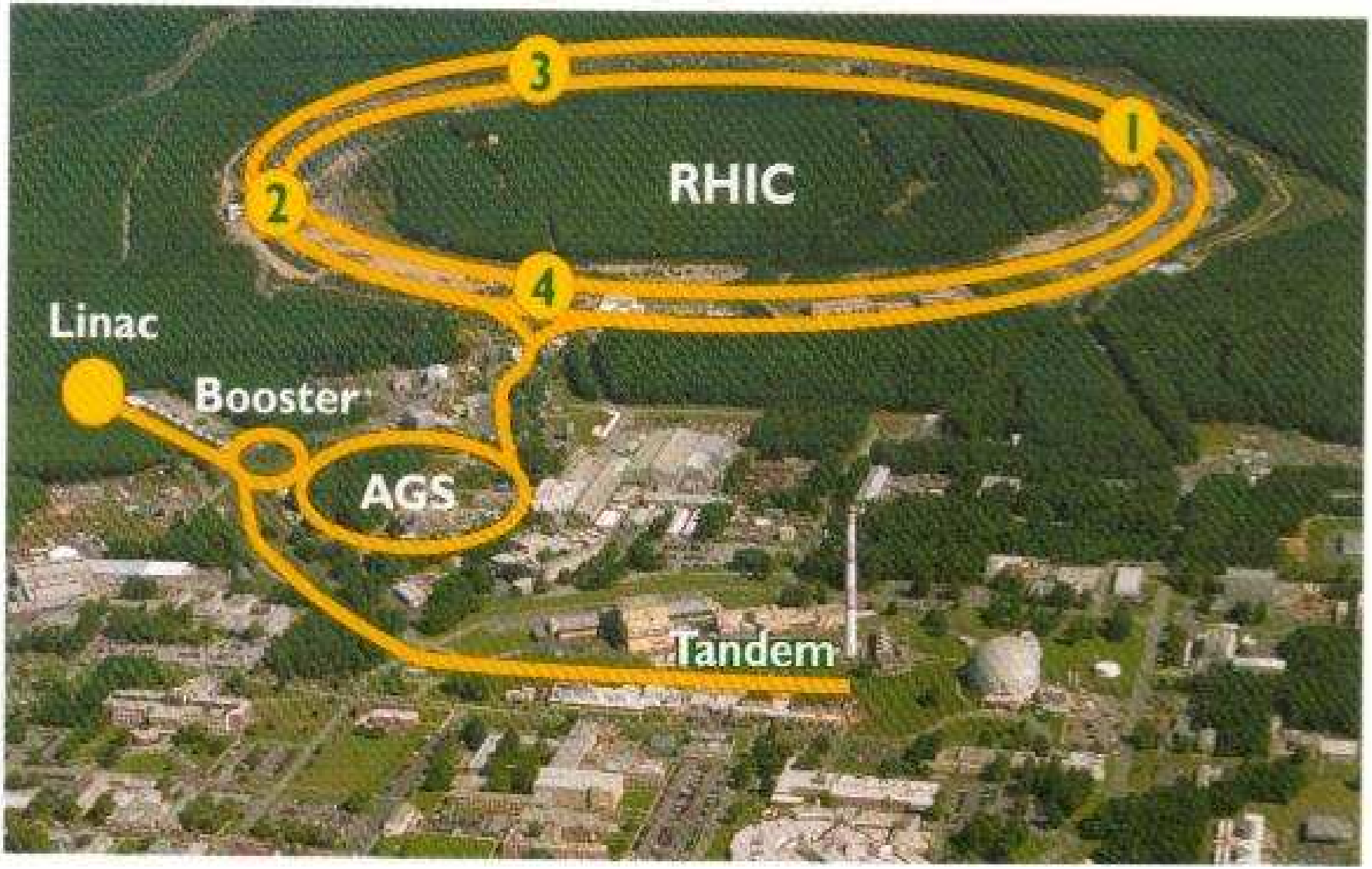
$$\Delta M_d / \Delta M_s \quad \Rightarrow \quad |V_{td}| / |V_{ts}|$$





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

The Experimental site at BNL.

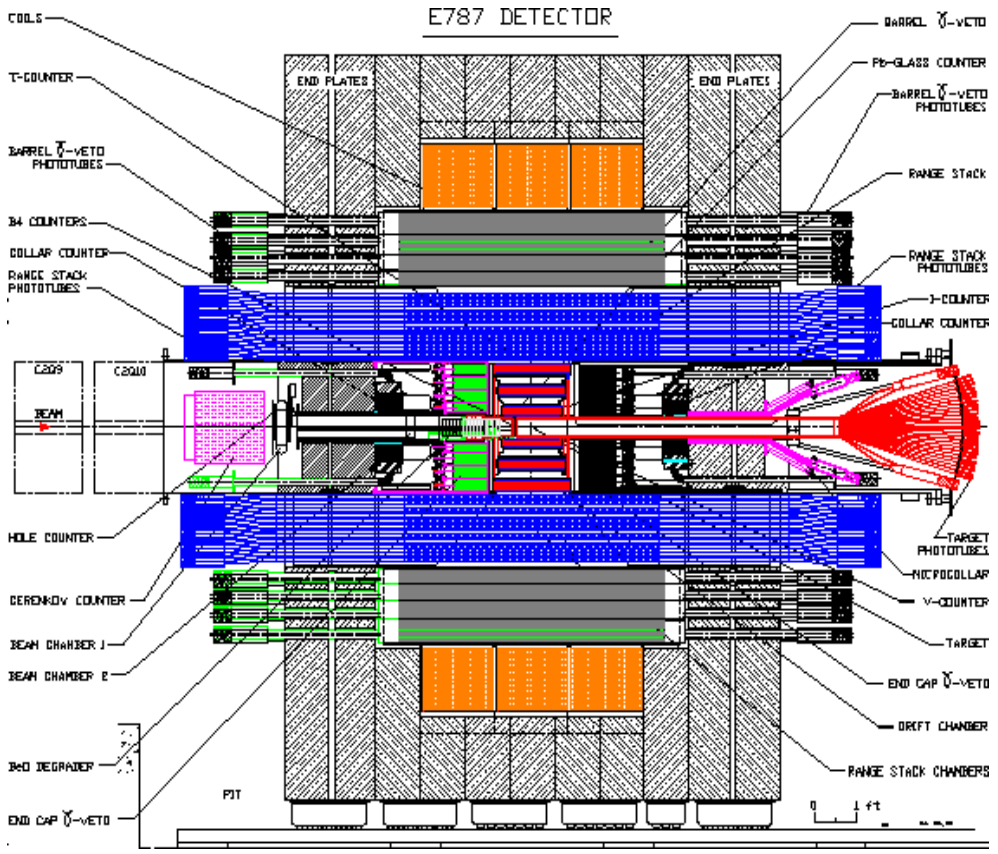


E787/E949 Detector and Technique.

BNL/Fukui Univ

/KEK/Princeton/Osaka/TRIUMF/Alberta/FermiLab/INR/IHEP/UNM

- 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.
- Charged track and momentum measured in Drift Chamber.
- Range, Energy and the decay $\pi \rightarrow \mu \rightarrow e$ is followed using 500 *MHz Transient Digitizers* in *Range Stack.*



10^6:1 π^0 rejection

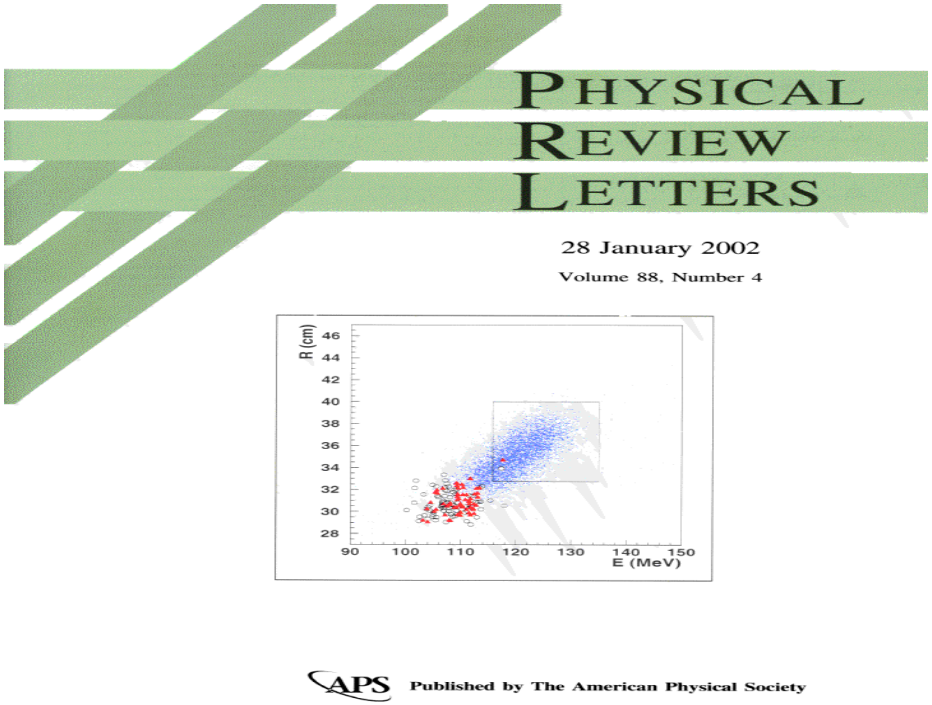
10^8:1 μ^+ rejection

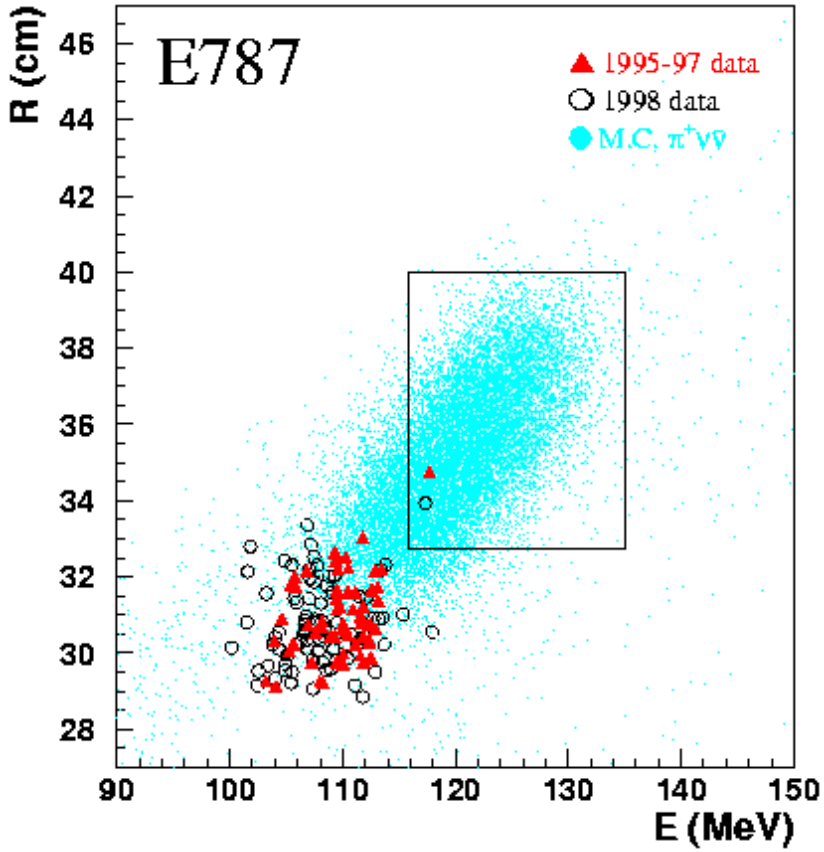
- Hermetic Photon vetoing via barrel (Pb-scint system) and CsI pure End Cap

Evidence for the Decay

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

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





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|.

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

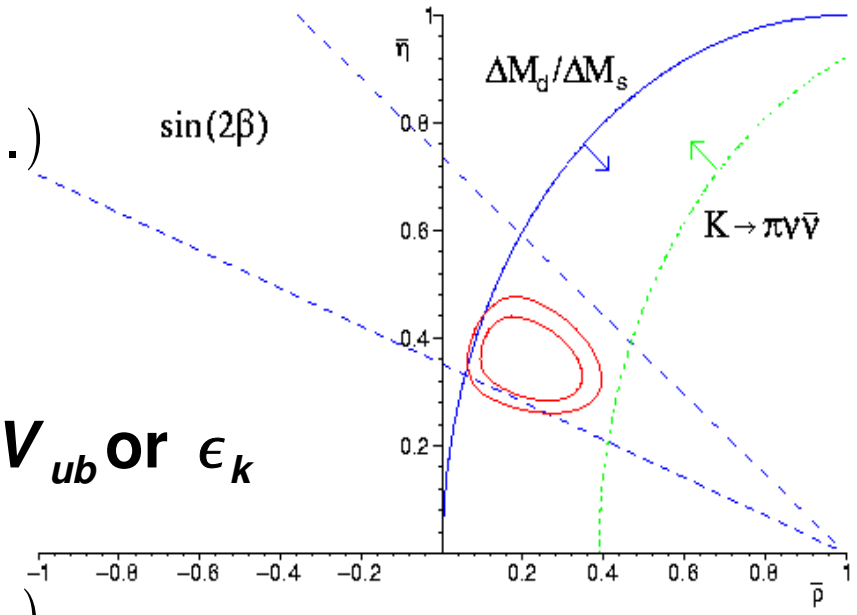
With $\overline{m}_t(m_t) = 166 \pm 5\, GeV/c^2$

$V_{cb} = 0.041 \pm 0.002$

Does not require knowledge of V_{ub} or ϵ_k

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

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



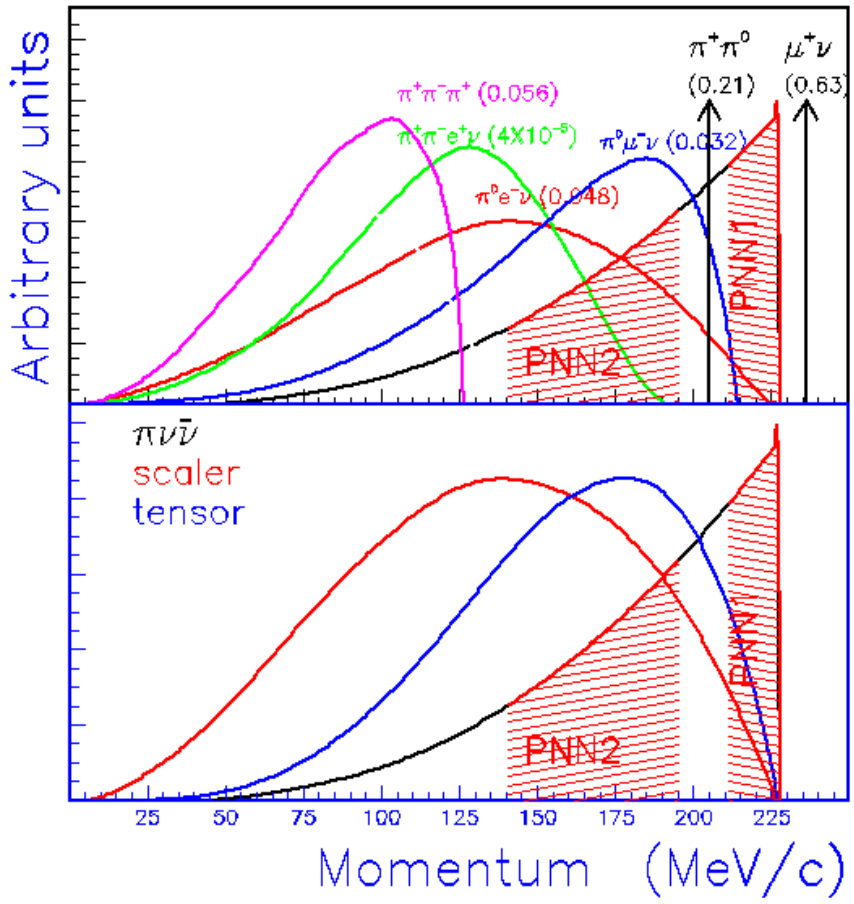
(Phys.Lett. B530 (2002) 108-116), hep-ph/0112135

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

$K^+ \to \pi^+ \nu \bar{\nu}$ At Lower Momentum.

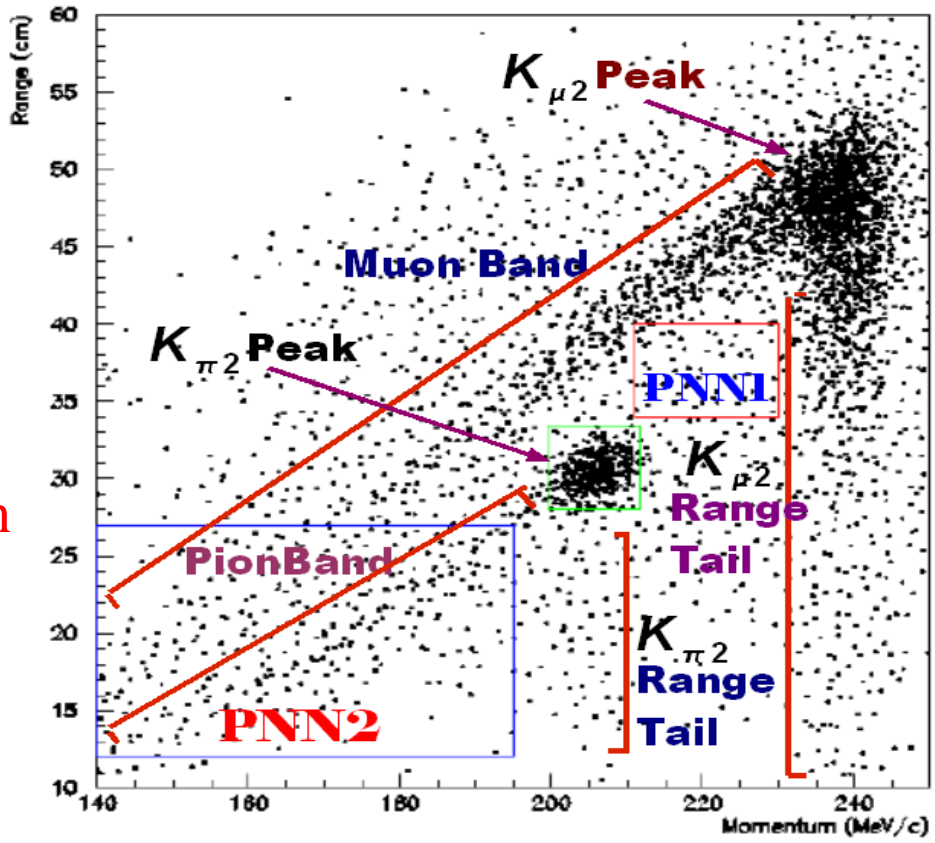
(Below the $K^+ \to \pi^+ \pi^0$ Peak)

- Much larger phase space acceptance below the $K_{\pi 2}$ 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



E787/E949 Data

* Events in $K_{\pi 2}$ and $K_{\mu 2}$ range tail are due to elastic (inelastic) scattering in the RS.



* Events in the muon band can arise from radiative $K_{\mu 2}$ or $K_{\mu 3}$ decay; $K_{\mu 2}$ decay in flight or $K_{\mu 2}$ decay with muon inelastic scattering in Target.

* Events in pion band can arise from beam pion scattering into the detector or pion from the $K_{\pi 2}$ decay due to inelastic scattering in the Target.

Offline Analysis.

* Blind Analysis:
  - Signal region is hidden (by inverting cuts) while cuts are developed and background levels are estimated.

  - Cuts against background are developed with a subset of the data (typically 1/3 of the data), but the effect of the cuts is measured (once) in an unbiased way on the remainder of the data.

* Birfurcated Analysis:
  - A priori identification of background sources.
  - Same dataset for background studies and signal searches.
  - Two independent cuts with high rejection for each background.
  - Measurement of background levels in the signal region at much less than 1 event level.

* Acceptance measured from data as much as possible. MC used only for trigger, solid angle and phase space.

* Crosscheck with measurement of Br($K^+ \to \pi^+ \pi^0$)

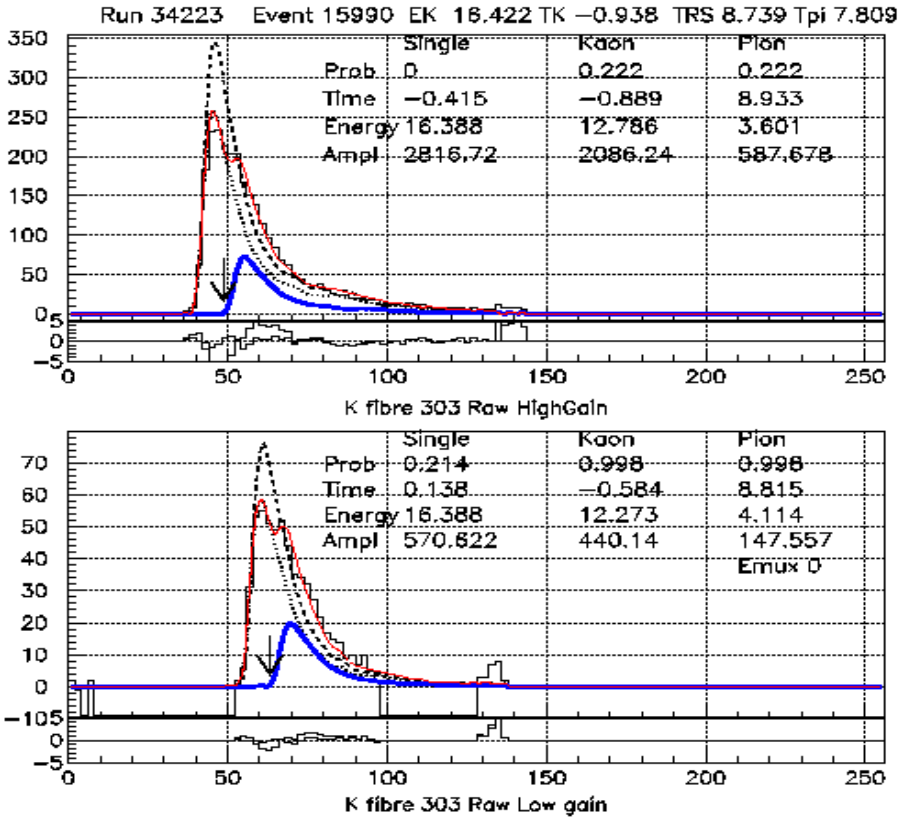
PNN2 Backgrounds

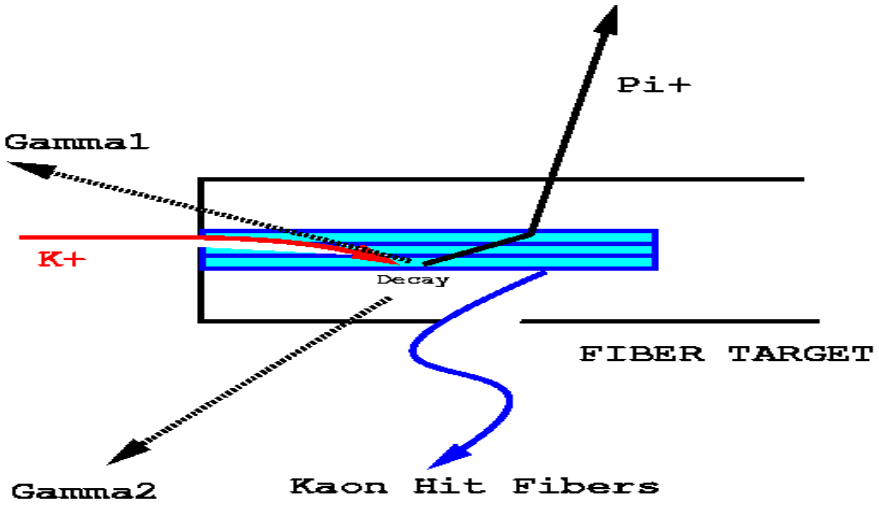
	Background Mechanism	Tools
1) $K^+ \to \pi^+ \pi^0$	: π^+ Scatters, Photons are lost.	Two Body Kinematics,Photon Veto, Detection of π^+ scattering in the target.
2) $K^+ \to \pi^+ \pi^- e^+ \nu_e$	: π^+ Spectra falls in the signal region. π^- Can disappear by absorption, e^+ can disappear by annihilation	Identify events in data, Use MC to test the performance of the cuts designed to find π^- and e^+ in the TG.
3) Beam Pions	: Pions in the beam can scatter into the detector.	K decay time in TG, Particle Identification in the Cerenkov Detector and Wire Chambers.
4) Radiative $K_{\mu 2}, K_{\mu 3}$	: Particle mis ID, Photons are lost.	Look for the decay chain $\pi^+ \to \mu^+ \to e^+$, Photon Veto
5) Radiative $K_{\pi 2}$	: Photons are lost.	Look for photons.Use both data and MC to measure this backgro -und
6) CEX	: $K^+ n \to K^0 p$ $K_L^0 \to \pi^+ l \nu_l (l = e, \mu)$	Delayed Coincidence cut is very effective. Use MC.

$K^+ \to \pi^+ \pi^0$ Background.

*Large background from $K^+ \to \pi^+ \pi^0$ in which the π^+ undergoes nuclear interaction in the plastic scintillator fiber target.

* Photons from π^0 lose the directional correlation with π^+ after π^+ scatters in the target.

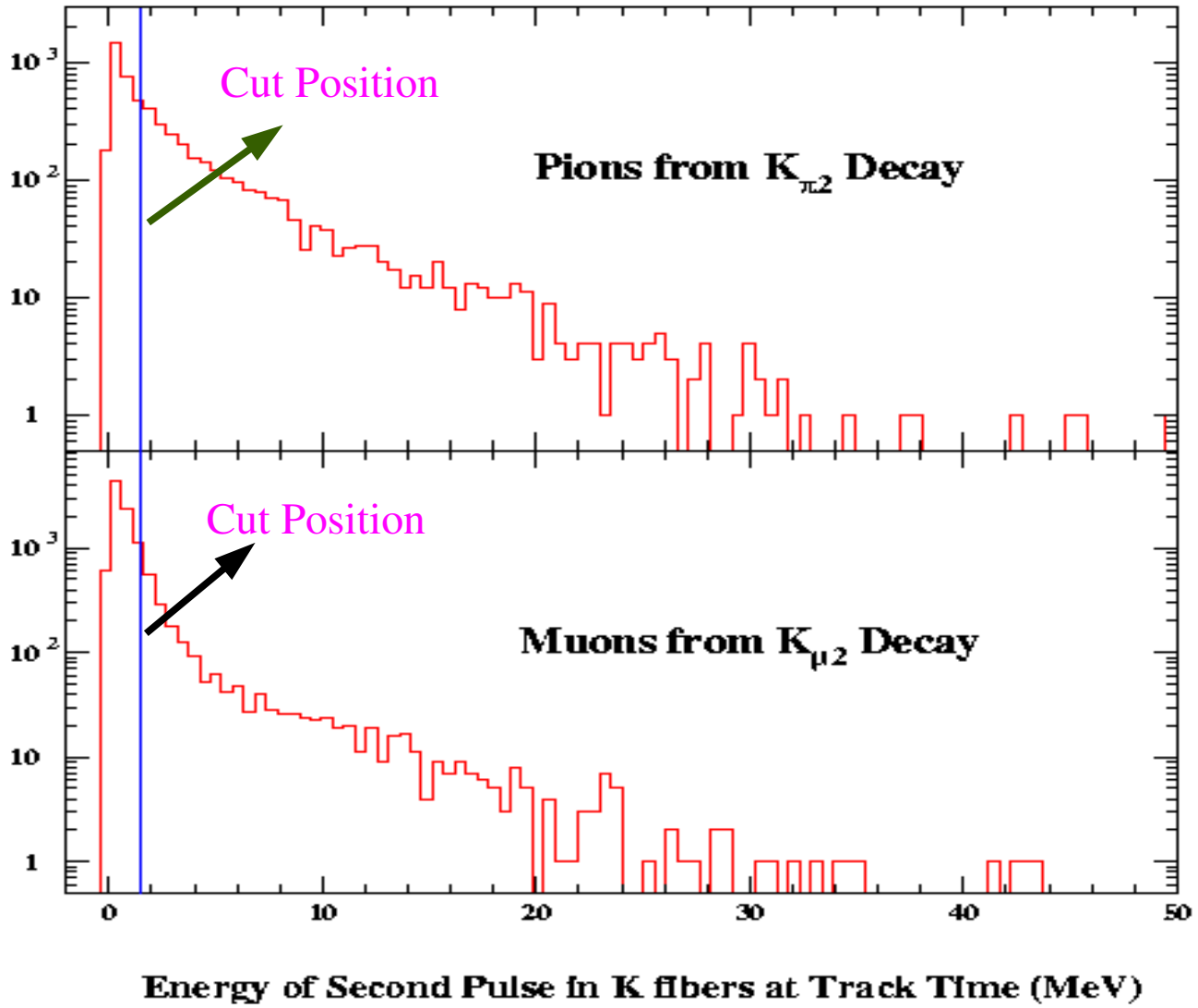




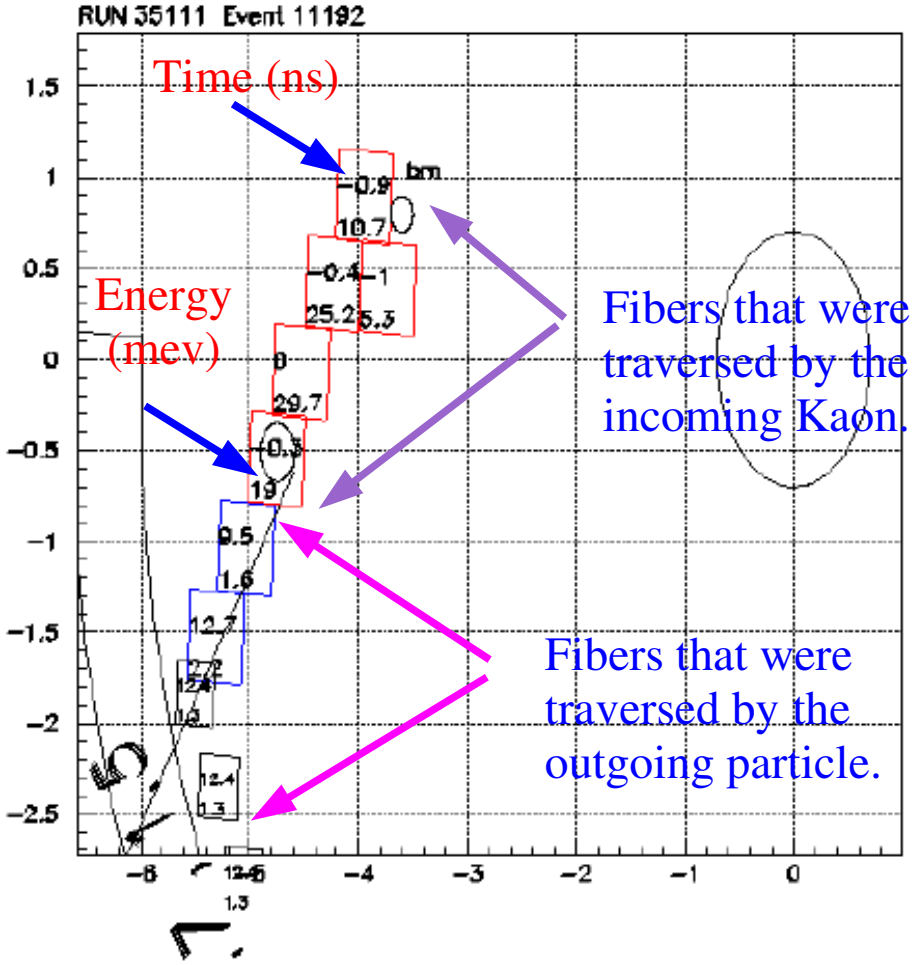
- Suppression of this background depends on the efficiency of finding evidence of pion scatter in the target.
- After reconstruction of pion and kaon, use CCD read out to find pion time pulses hidden under K-fibers.

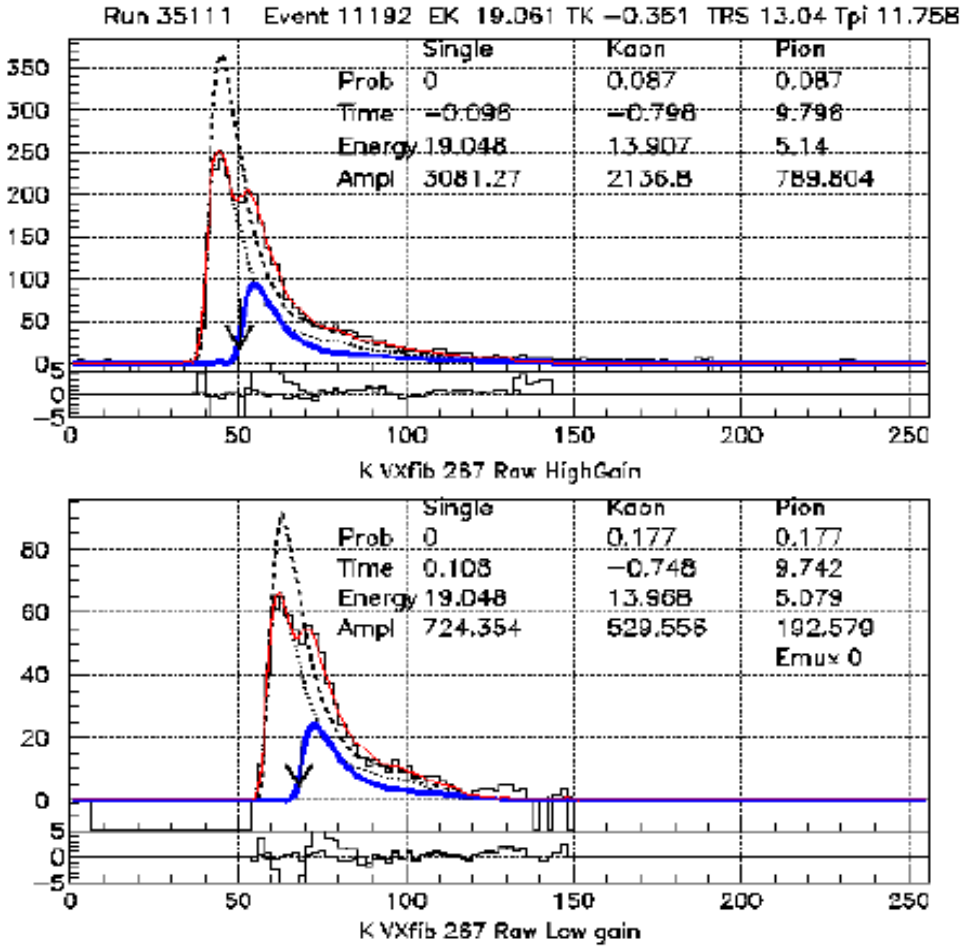
* Measure the Normalization on a sample tagged by Photons and measure the rejction of the Photon Veto cuts on a sample tagged by cuts that were designed to find pion scatter in the Target.

Finding pion scatter in the Target



$K_{\pi 2}$ Scatter Candidate





Ke4 Background in the PNN2 region

- $Br(K^+ \to \pi^+ \pi^- e^+ \nu) : 4 \times 10^{-5}$

  a) No Photons in the final state to veto.

  b) π^- can disappear by absorption.

  c) e^+ can disappear by annihilation.

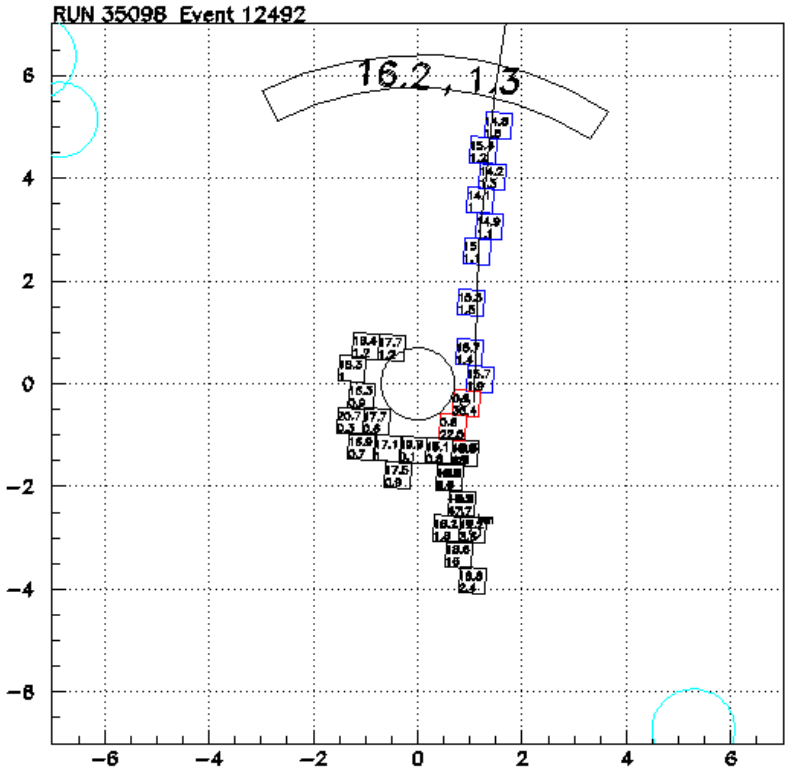
  d) π^+ momentum falls in the momentum region 150 to190 MeV/c

- Background Measurement :

  a) Measure the Normalization (from data) by tagging events with extra energy in the target not belonging to either kaon or positive pion.

  c) Use Monte Carlo to measure the Rejection of cuts designed to find extra energy in the Target belonging to the negative pion and the positron.

  (Rejection =58)

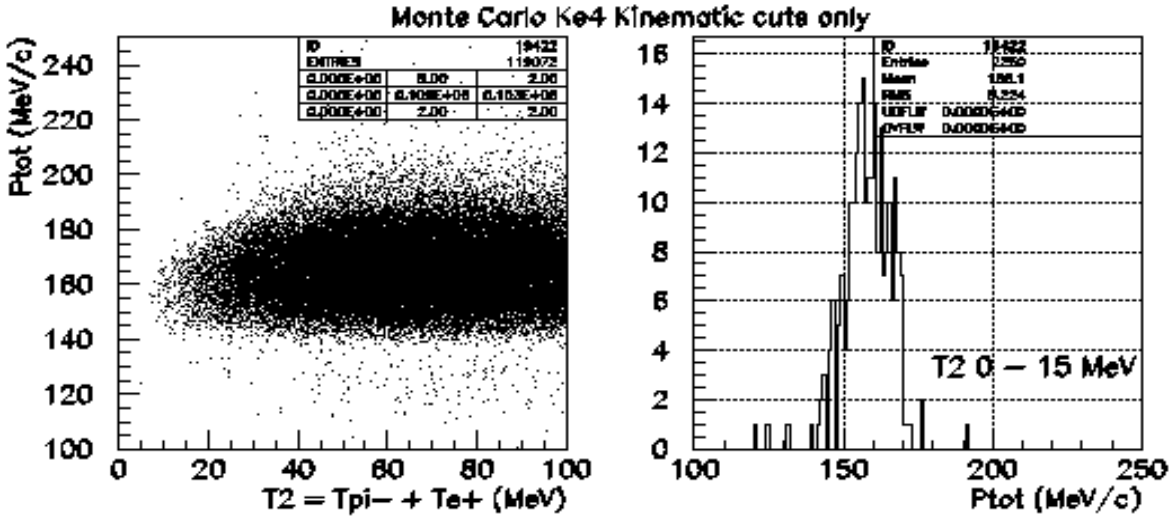


d) Fortunately the phase space for the decay vanishes as kinetic energy of π^- and e^+ goes to 0

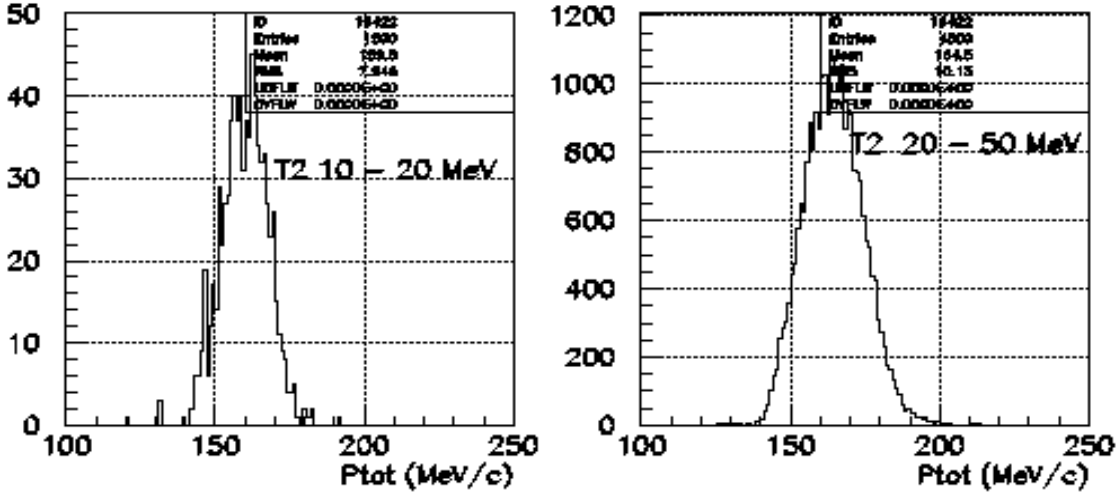
Ke4 Background (Cont.)

Monte Carlo of

$K^+ \to \pi^+ \pi^- e^+ \nu_e$.



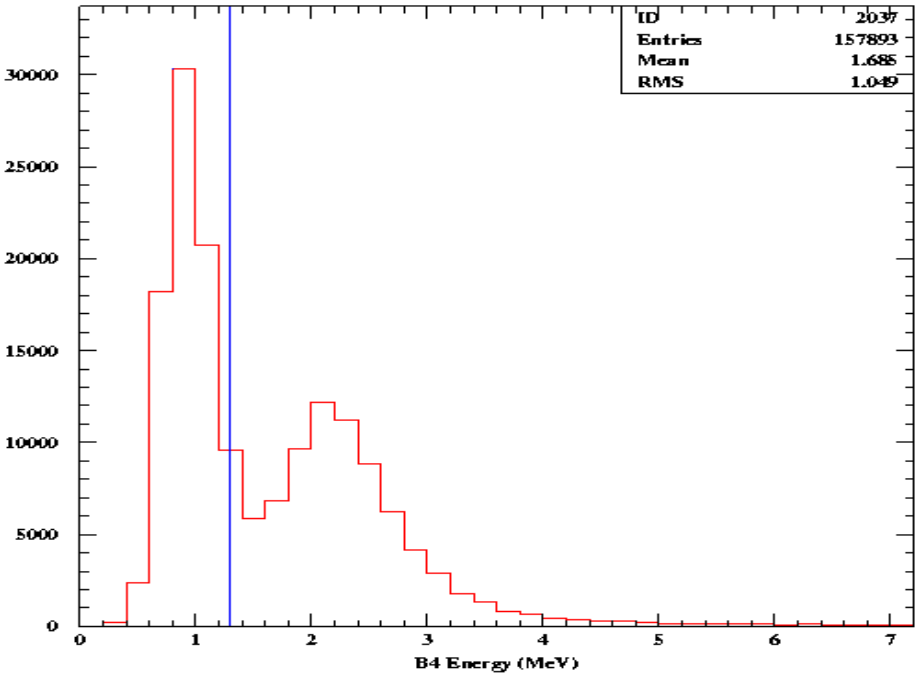
Reconstructed momentum of π^+ versus the kinetic energy of π^- and e^+ .

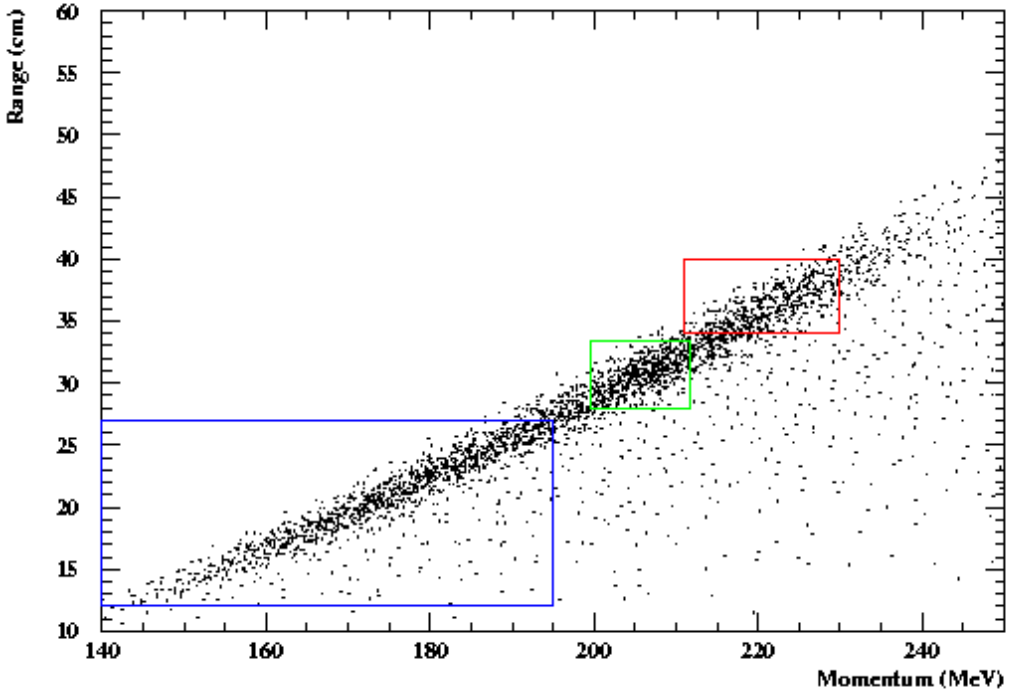


Beam Backgrounds

* Background Source:
  K decay in Flight, Single pion entering the Detector.

* Tools: Identification of Beam Particles in the B4 Hodoscope and a delayed coincidence cut of 6 ns between the incoming particle and the outgoing track particle at the target.





Positive identification of incoming beam particles by the Cerenkov Detector and theWire Chambers.

Total Background in PNN2 region

	1996		1997
No. of K^+ stopped in TG:	1.12×10^{12}		0.61×10^{12}
Background			
1) $K^+\to\pi^+\pi^0$	0.630 ± 0.170	(Data)	0.399 ± 0.150
2) $K^+\to\pi^+\pi^0\gamma$	0.027 ± 0.004	(Data + MC)	0.006 ± 0.002
3) $K_{\mu2\gamma}+K_{\mu3}$	0.007 ± 0.007	(Data)	0.009 ± 0.009
4) Beam	0.033 ± 0.033	(Data)	0.033 ± 0.033
5) $K^+\to\pi^+\pi^-e^+\nu_e$	0.026 ± 0.032	(Data + MC)	0.026 ± 0.026
6) CEX	0.011 ± 0.011	(MC)	0.013 ± 0.013
Total Background	0.734 ± 0.177		0.486 ± 0.160

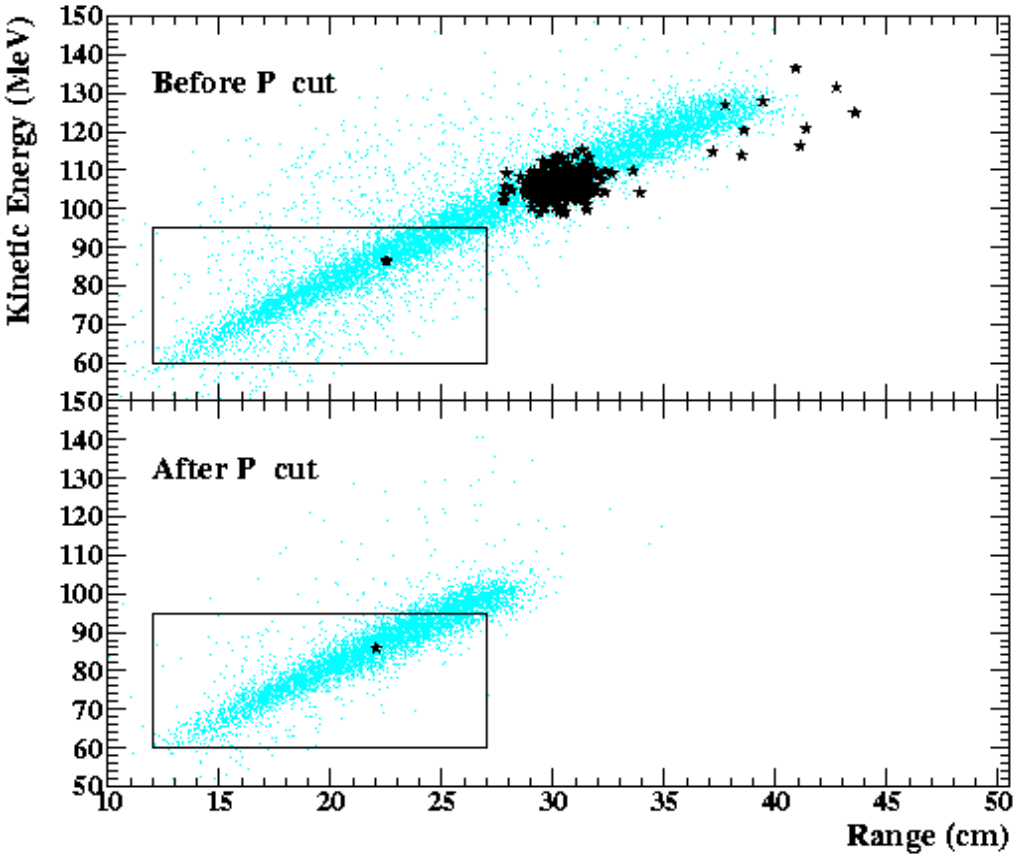
Acceptance Factors in PNN2 region.

	1996	1997
1) K^+ Stop Efficiency	0.670	0.708
2) Time Consistency Cuts	0.591	0.675
3) $K^+ \to \pi^+ \nu \bar{\nu}$ Phase Space	0.345	0.345
4) Geometry	0.317	0.312
5) π^+ Nucl. Int. and decay in flight	0.708	0.708
6) Reconstruction Efficiency	0.957	0.944
7) Kinematic Cuts	0.686	0.697
8) $\pi \to \mu \to e$ decay chain	0.545	0.490
9) Beam and Target analysis	0.479	0.492
10) CCD Acceptance	0.401	0.431
11) Accidental Loss	0.363	0.390
Total Acceptance	7.65×10^{-4}	9.71×10^{-4}

Results from PNN2 Region

1996: K Stop in TG: 1.12×10^{12}

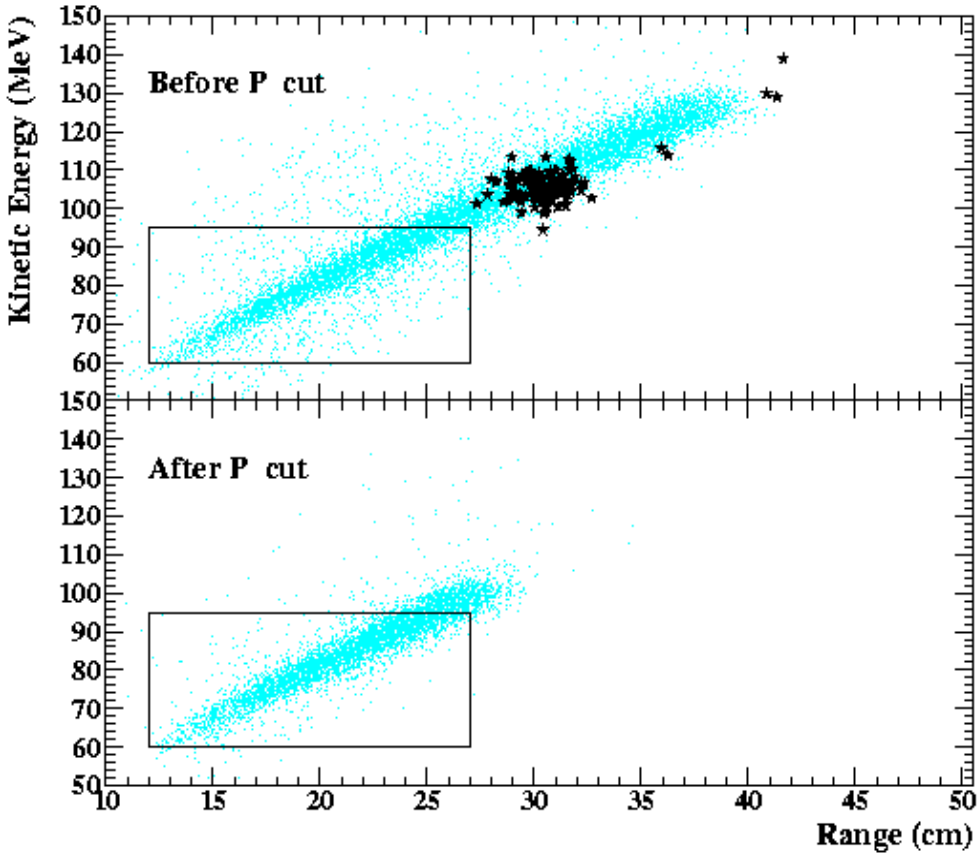
PL B 537. 211 (2002)



Total Background = 0.73

Total Acceptance = 7.65×10^{-4}

1997: K Stop in TG: 0.61×10^{12}

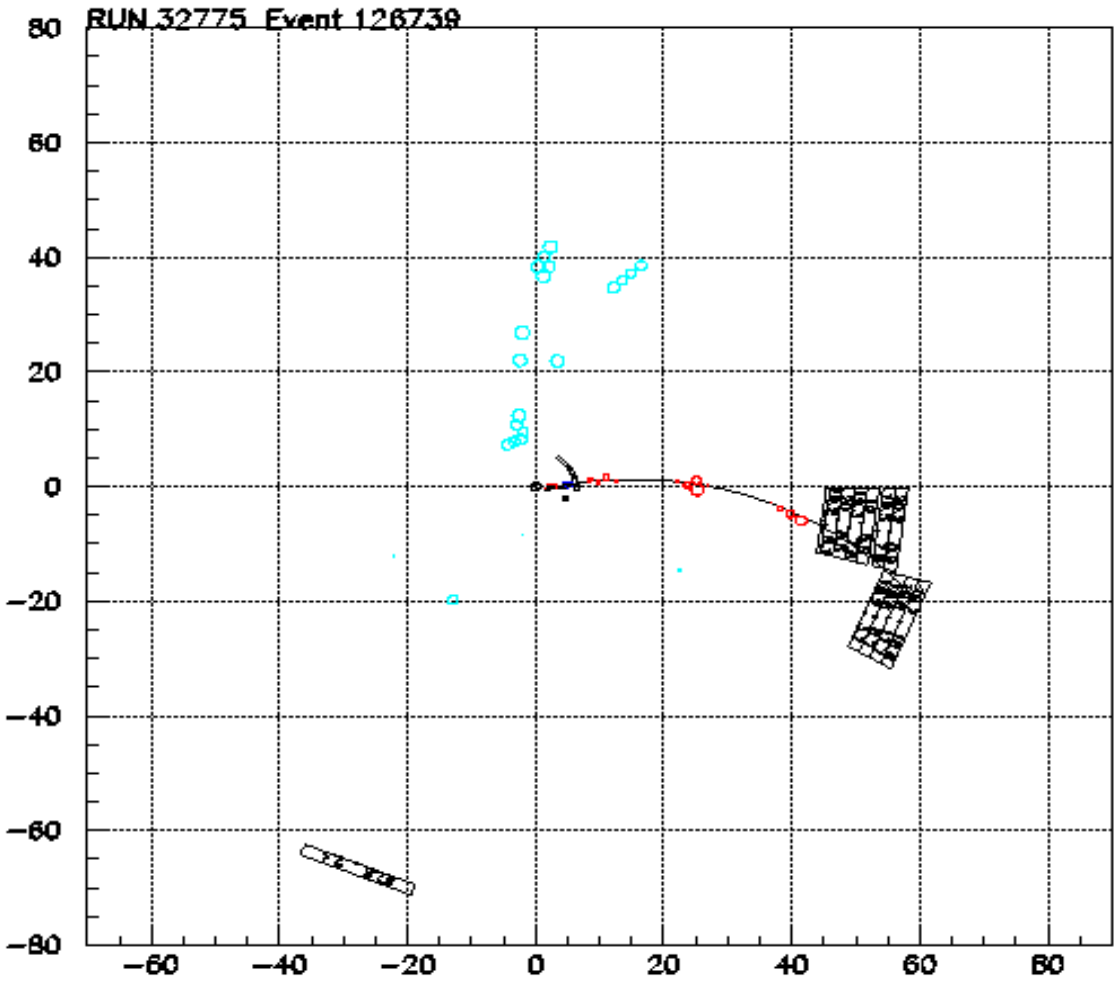


Total Background = 0.48

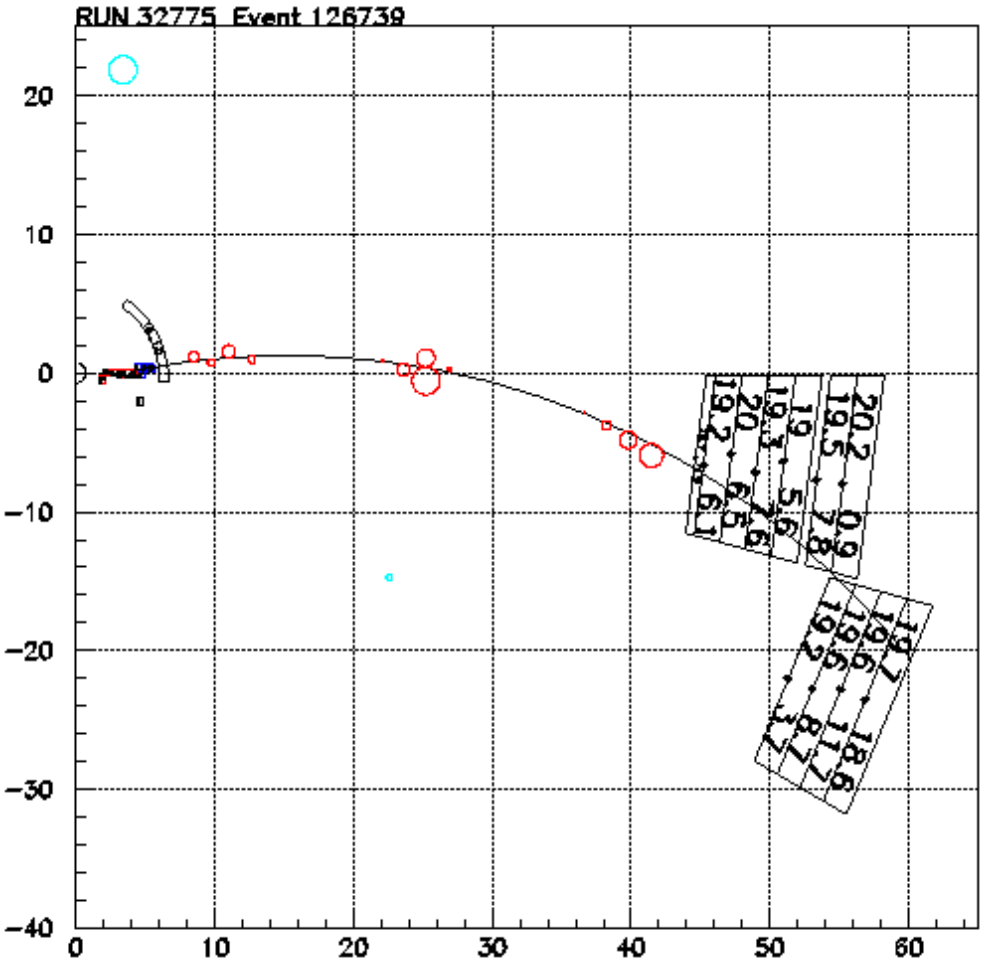
Total Acceptance = 9.71×10^{-4}

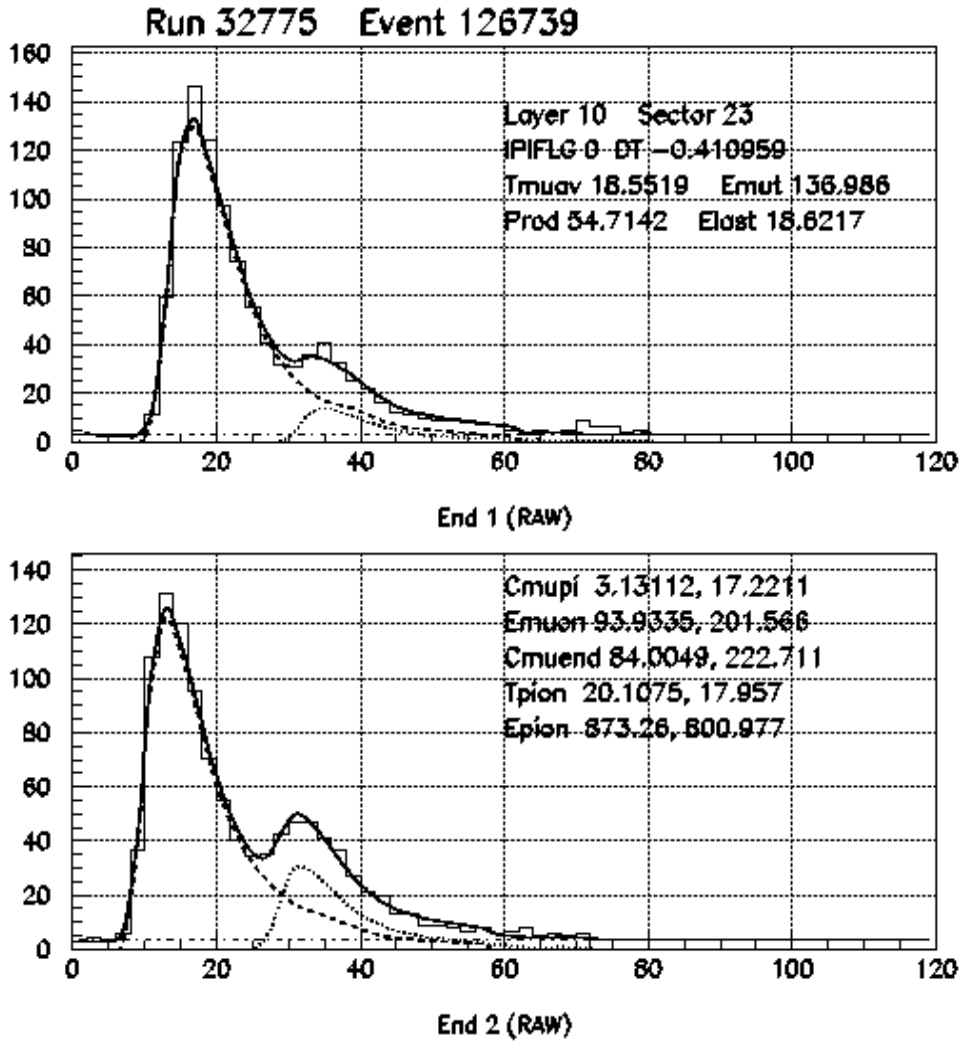
Combined Sensitivity = $(6.87\pm0.036)\times10^{-10}$

The candidate event in 1996 data set

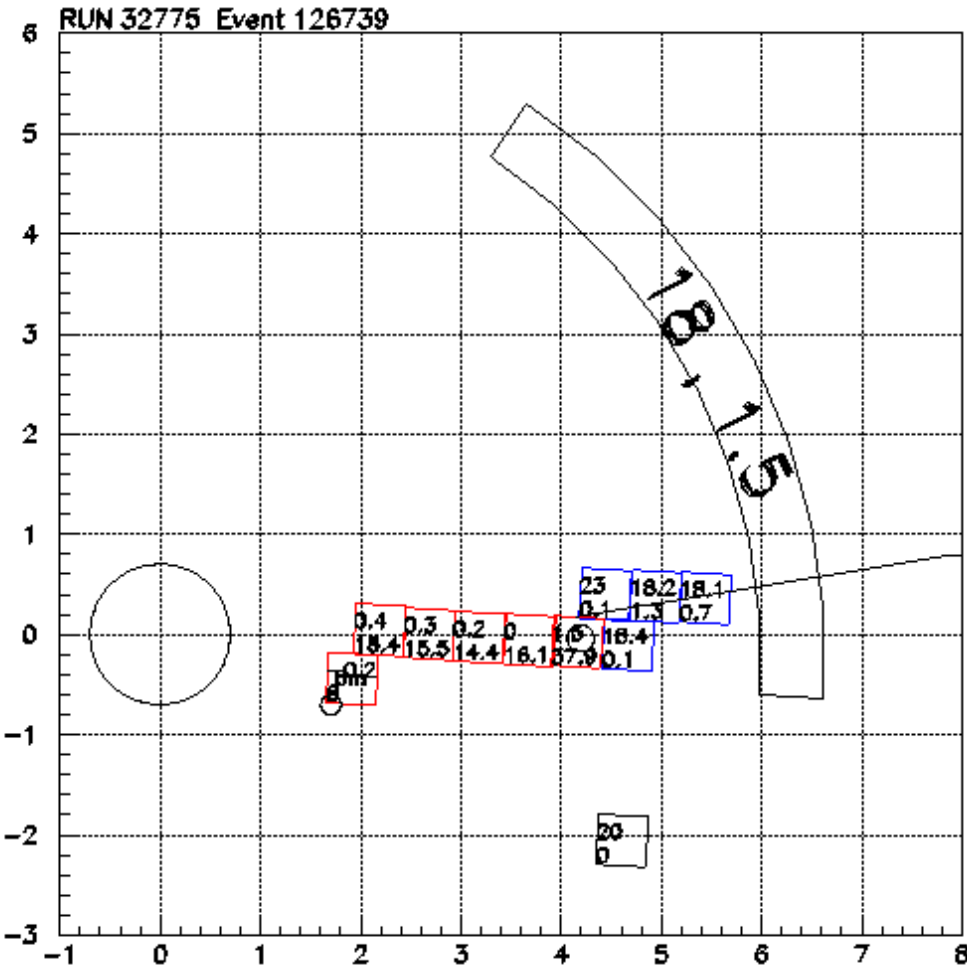


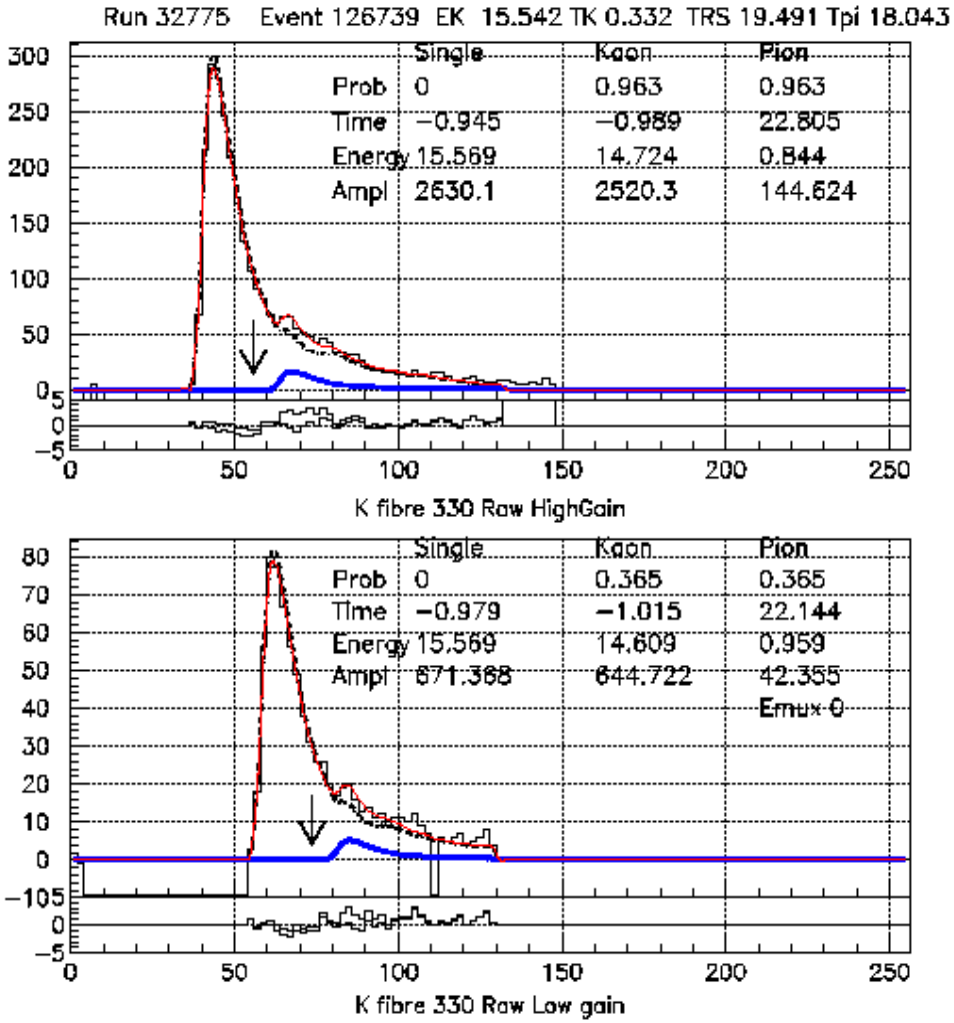
1996 Candidate event (cont.)



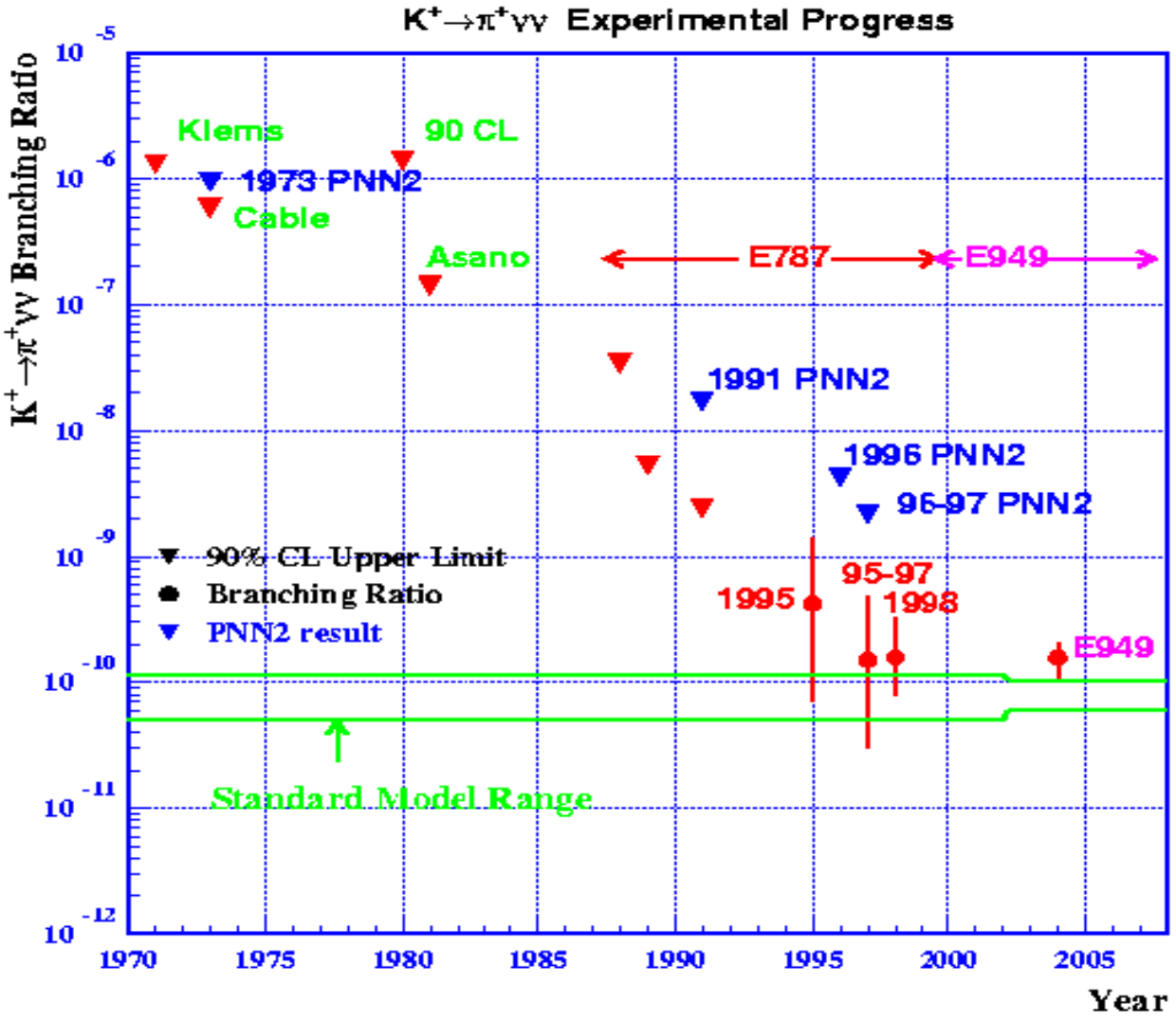


1996 Candidate event (cont.)





Results from E787 and Progress.



Is there Scalar or Tensor Interaction..

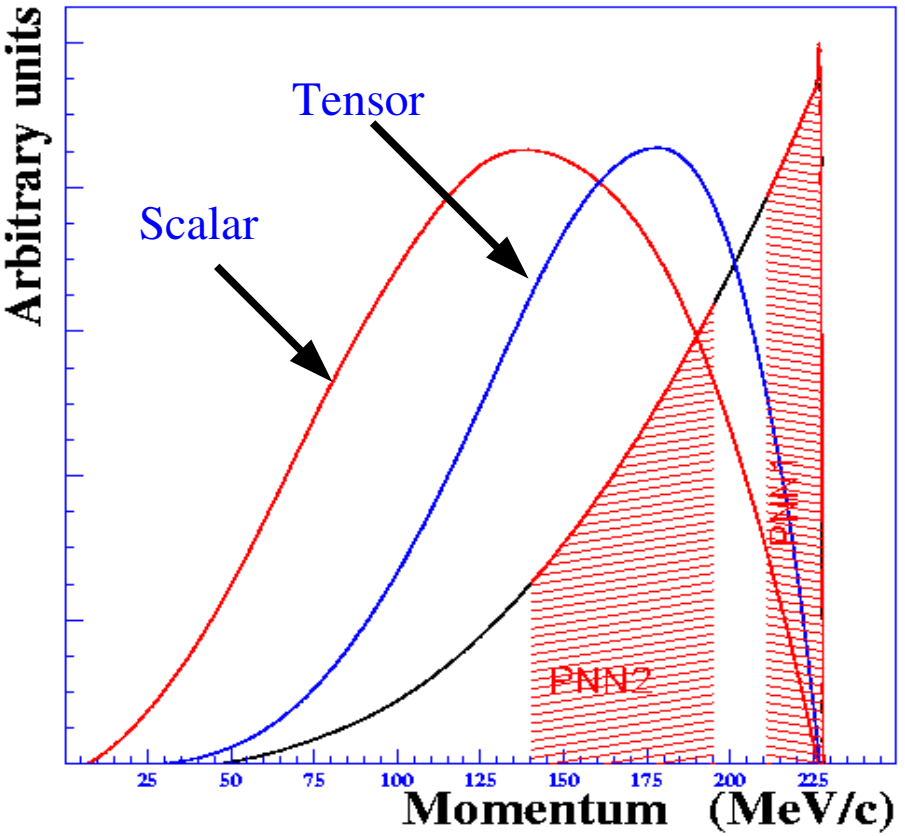
* Scalar Interaction:

Sensitivity = $(8.747 \pm 0.04) \times 10^{-10}$

Observation of 1 event with expected background of 1.22 =>

$$B(K^+ \to \pi^+ X^1 X^2) < 2.75 \times 10^{-9}$$

(90% CL) (FC)



* Tensor Interaction:

Sensitivity = $(5.82 \pm 0.04) \times 10^{-10}$

Observation of 1 event with expected background of 1.22 =>

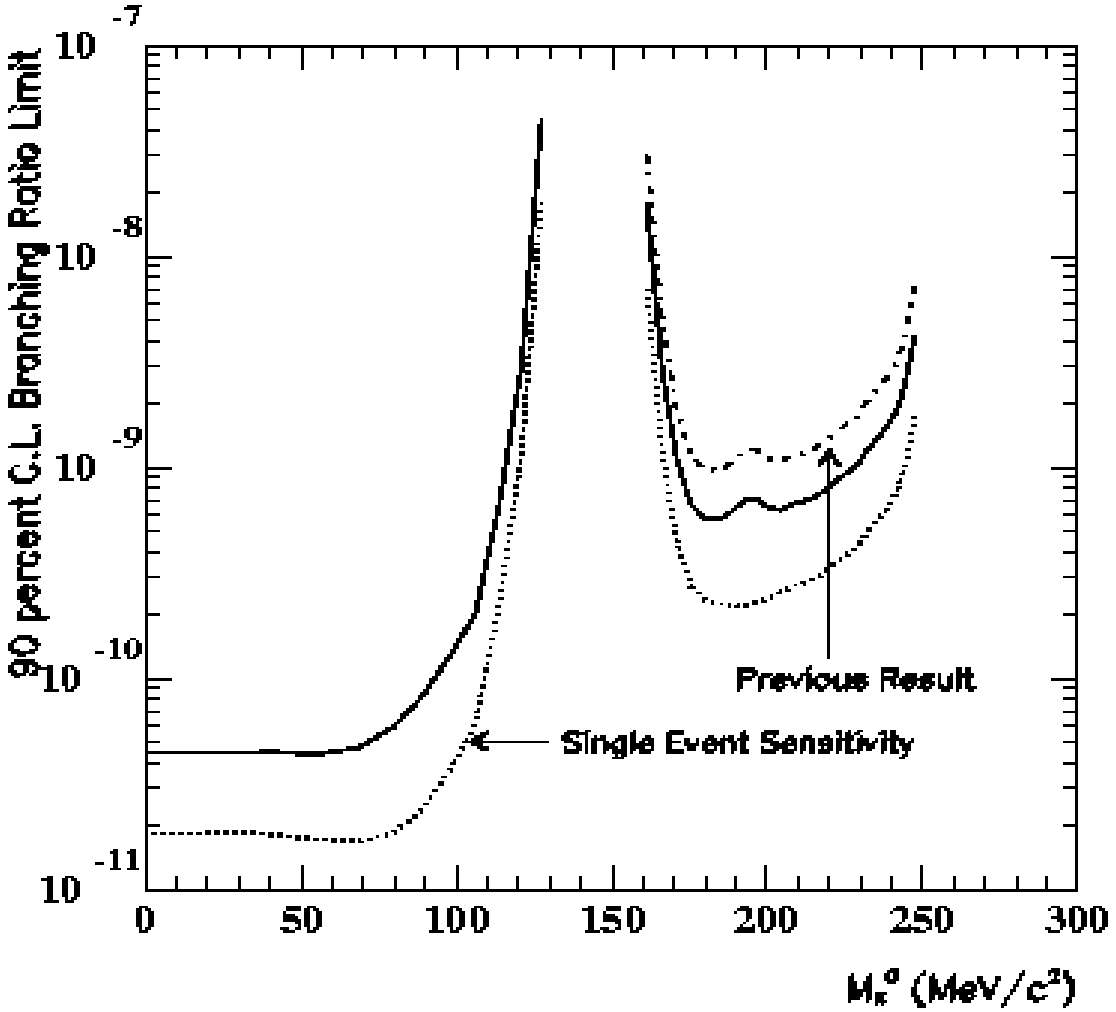
$$B(K^+ \to \pi^+ X^1 X^2) < 1.83 \times 10^{-9}$$

(90% CL) (FC)

The Decay $K^+ \to \pi^+ X^0$

Single Event Sensitivity =

1/(Total K exposure * Total Acceptance)

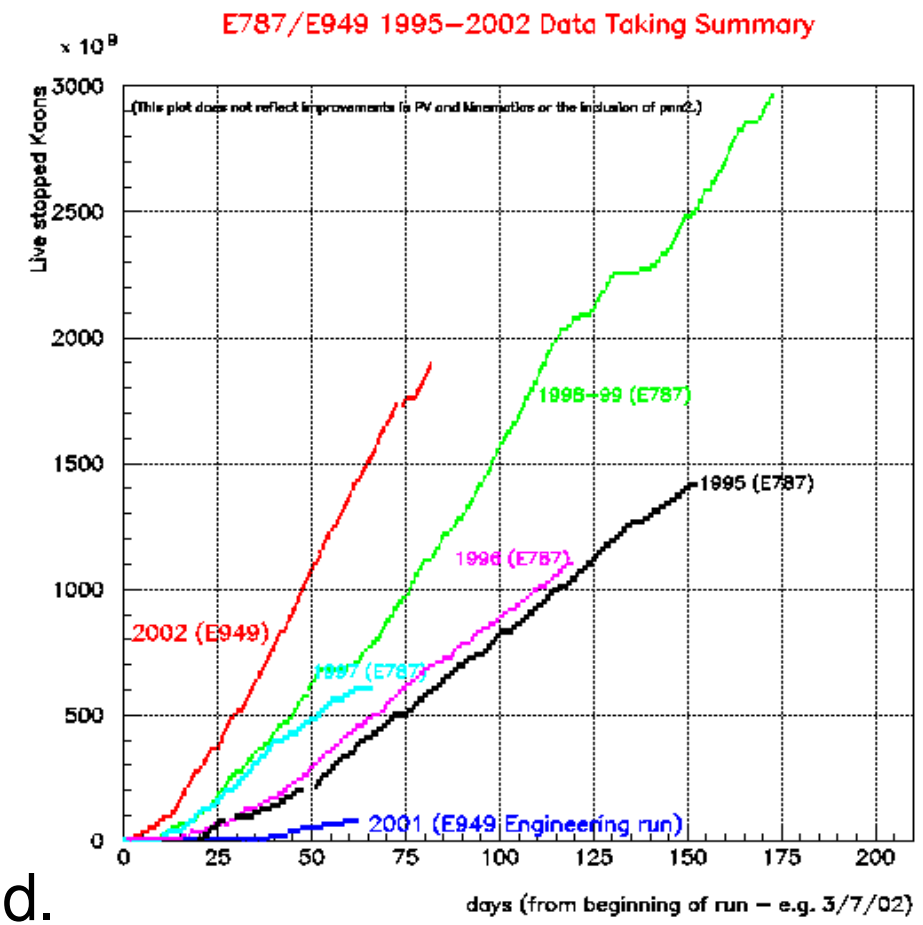


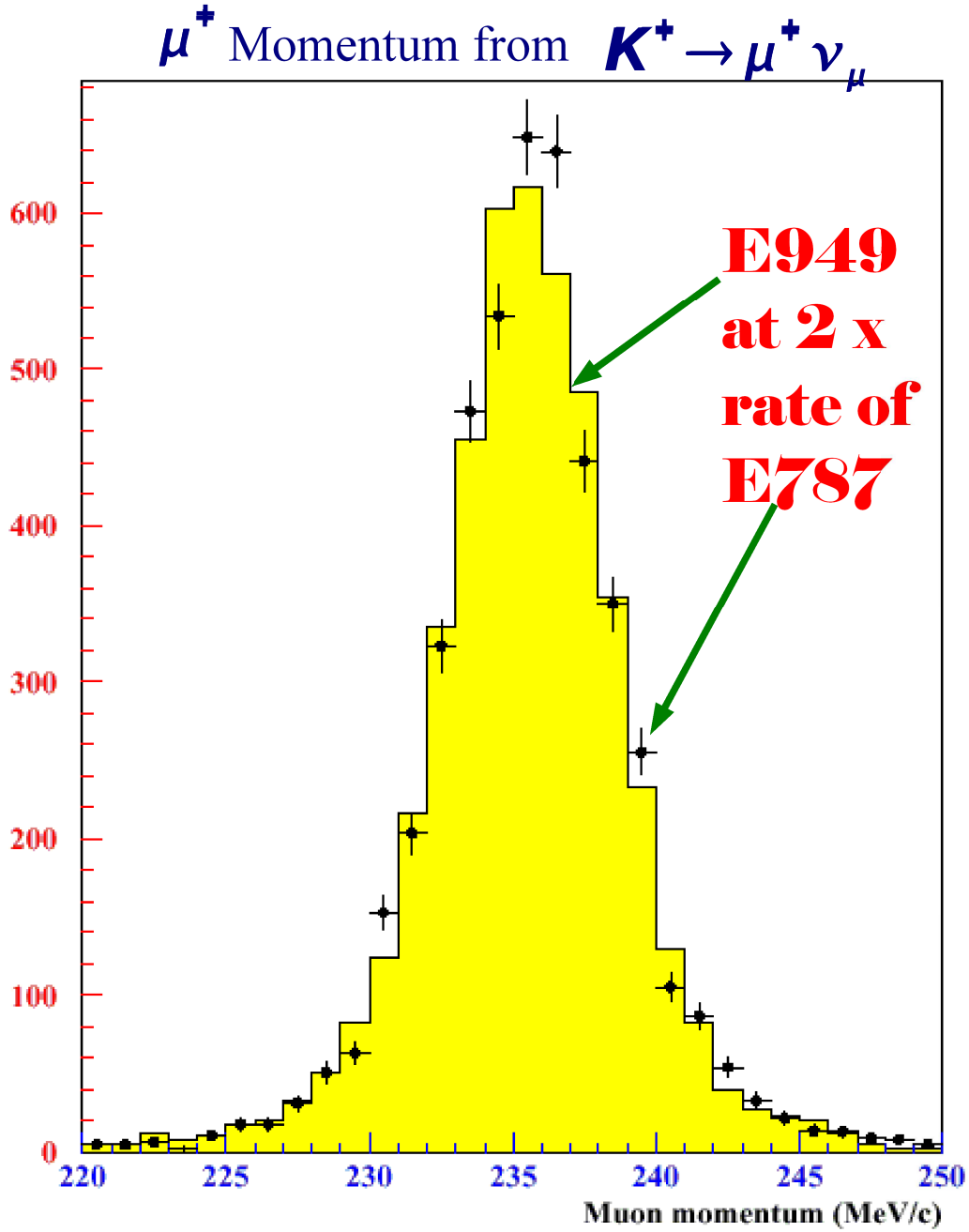
E949 At AGS.

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

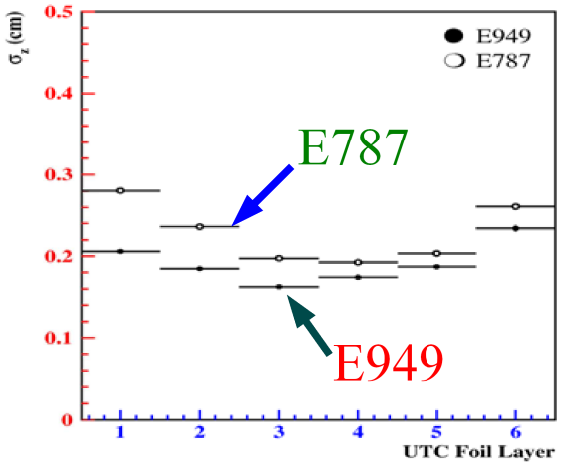
  $\Rightarrow$

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

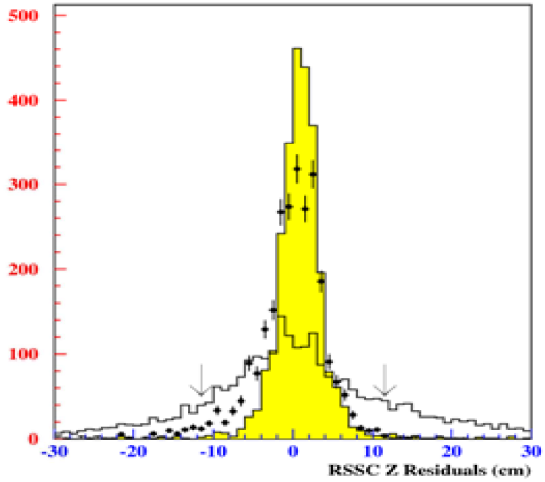




Improved Z-resolution in UTC



Range Stack Straw Chamber Tracking improved by 5 x.



Prospect of PNN2 at E949

* Improvement in the Photon Detection efficiency is necessary to search for this rare decay in the PNN2 region, where the $K^+ \to \pi^+ \pi^0$ decay is the main source of background.

* E949 needs another factor of ~5 background reduction in the PNN2 region to achieve the signal to noise ratio of 1, with the measured branching ratio of $\mathbf{1.57 \times 10^{-10}}$.

* With the new photon detectors at E949, we might achieve that factor of ~5 background reduction in the PNN2 region.

Conclusion

- E787 observed two signal 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

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

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

- Major new efforts are 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. We have analysed the 1996 and 1997 data sets in the lower pion momentum region. Results from the 1996 data set are already published. The results from the 1997 data set will be published soon.

- E949 ran for about 12 weeks in early 2002. Analysis is in progress. With the improvements in the detector performance, the results from E949 could be exciting in both lower and higher pion momentum region.

Rare K decays are going to play a major role in Particle Physics in the next 10-15 years with more challenging experiments likeE391a (KEK), KOPIO (BNL), CKM (Fermi Lab) coming up.