The Rare Decay $K^+ \to \pi^+ \nu\overline{\nu}$ at BNL E787

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- Motivation
- E787
- Evidence for $K^+ \to \pi^+ \nu\overline{\nu}$
- Recent progress

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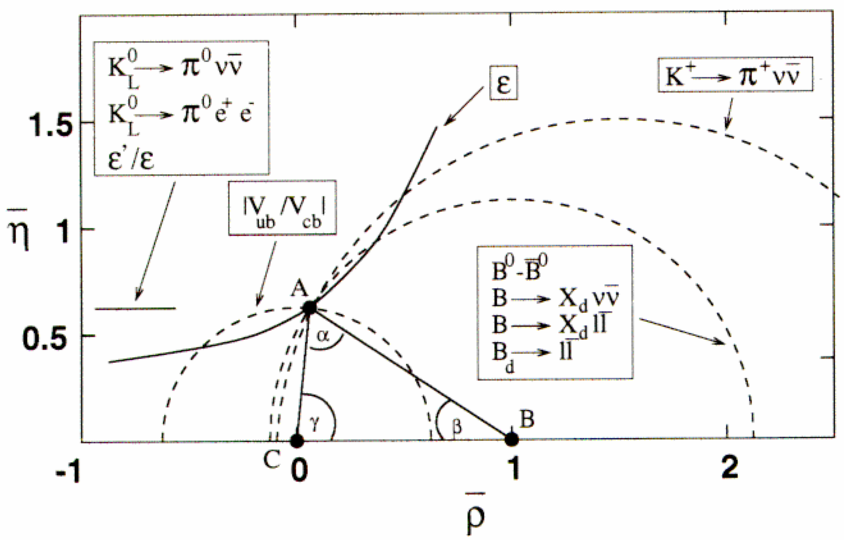
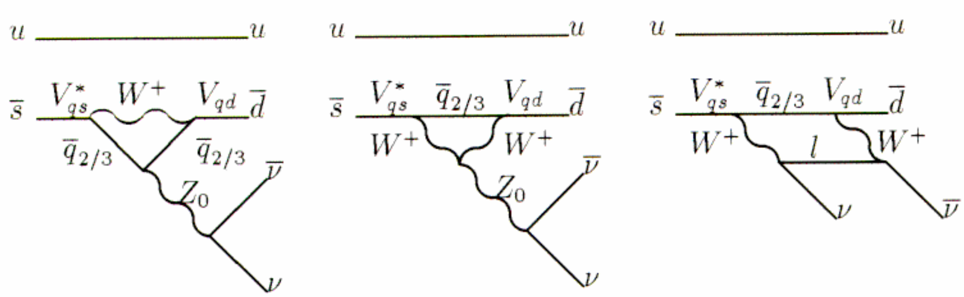
- In the SM: Quark Mixing – CP Violation
- Exploration of this relationship between two longstanding mysteries of particle physics is a major theme of experimental work over the next decade.



Buras *et al.* hep-ph/9704376

- $K^+ \to \pi^+ \nu\bar{\nu}$ $\Rightarrow$ Theoretically clean determination of $|V_{td}|$



- Top quark dominates in loops
- Hadronic matrix element: $< K|H|\pi >$ from BR($K^+ \to \pi^0 e^+ \nu_e$)
- "Long-distance" contributions suppressed by $> 10^3$
- Charm contribution uncertainty to $|V_{td}| \sim 4\%$

$K^+ \to \pi^+ \nu\overline{\nu}$: The Standard Model "Standard"[1] (?)

It is commonly heard that "new" physics will not contribute significantly to BR($K^+ \to \pi^+ \nu\overline{\nu}$), given current constraints from other measurements.

In this view, $K^+ \to \pi^+ \nu\overline{\nu}$ serves as a high-precision SM standard with which to confront measurements in the B sector where "new" physics might be more manifest.

This gets a bit murky since it depends somewhat on how "natural" an extension to the SM we are talking about.

Some examples of $K^+ \to \pi^+ \nu\overline{\nu}$ beyond the SM:

- FCNC from higher energy scale
  - SUSY
    - R-parity violating.[2] Was of recent topical interest due to high Q^2 events at HERA.
    - R-parity non-violating (many papers).[3] Factor 2-3 above SM level still possible.
  - Topcolor models[4]

[1] Bigi and Gabbiani, Nucl. Phys. B367, 1991
[2] Agashe and Graesser, PRD 54 (1996) 4445)
[3] e.g. Nir and Worah, Phys. Lett B423 (1998) 319. Buras, Romanino and Silvestrini, Nucl. Phys. B520 (1998) 3.
[4] Buchalla, Burdman, Hill and Kominis, Phys. Rev. D53 (1996), 5185

- $K^+ \to \pi^+ X^0$, where X^0 is Nambu-Goldstone boson from breaking some global symmetry. Indistinguishable from $K^+ \to \pi^+ \nu\overline{\nu}$, except for 2-body kinematics.
  - Familon:[5] Nambu-Goldstone boson from breaking global family symmetry

    $$\mathrm{BR}(K^+ \to \pi^+ f) = 2.7 \times 10^{13}\ \mathrm{GeV}^2/\mathrm{F}^2_{\mathrm{K}\pi}$$

    $$10^{11}\ \mathrm{GeV} < \mathrm{F}_{\mathrm{K}\pi} < 10^{12}\ \mathrm{GeV} \quad \text{from cosmology}$$

    $$\Rightarrow \mathrm{BR}(\mathrm{K}^+ \to \pi^+\mathrm{f}) >\sim 10^{-11}$$

  - Certain axion models.[6]

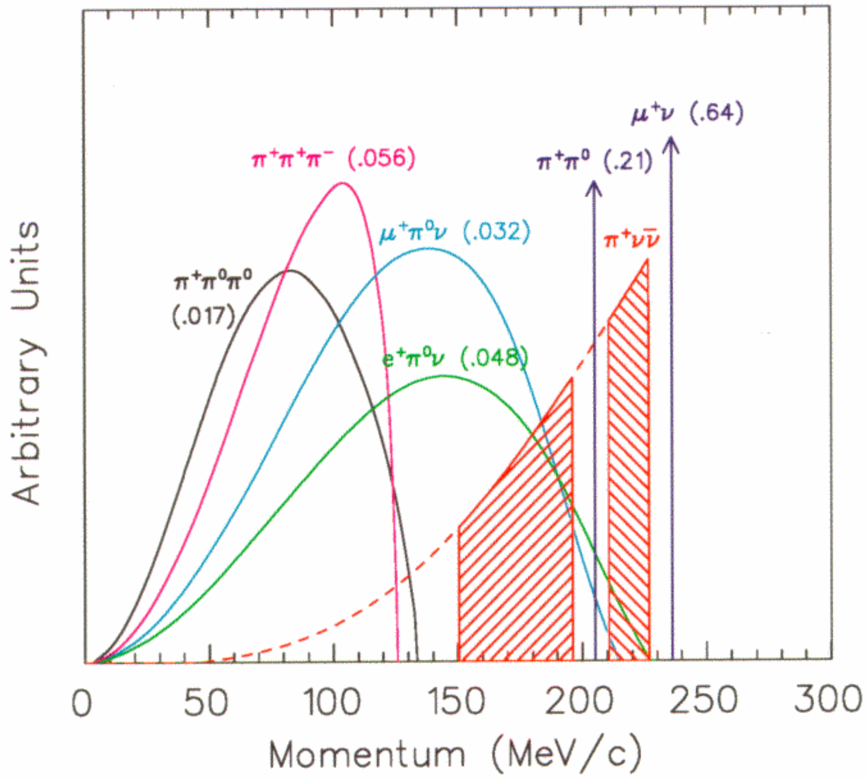
Viewed from a different angle:

- Opportunity for significant experimental improvement.
- Experimental challenge; > 25 years of non-observation (now coming to an end)

[5] F. Wilczek, PRL 49 (1982) 1549

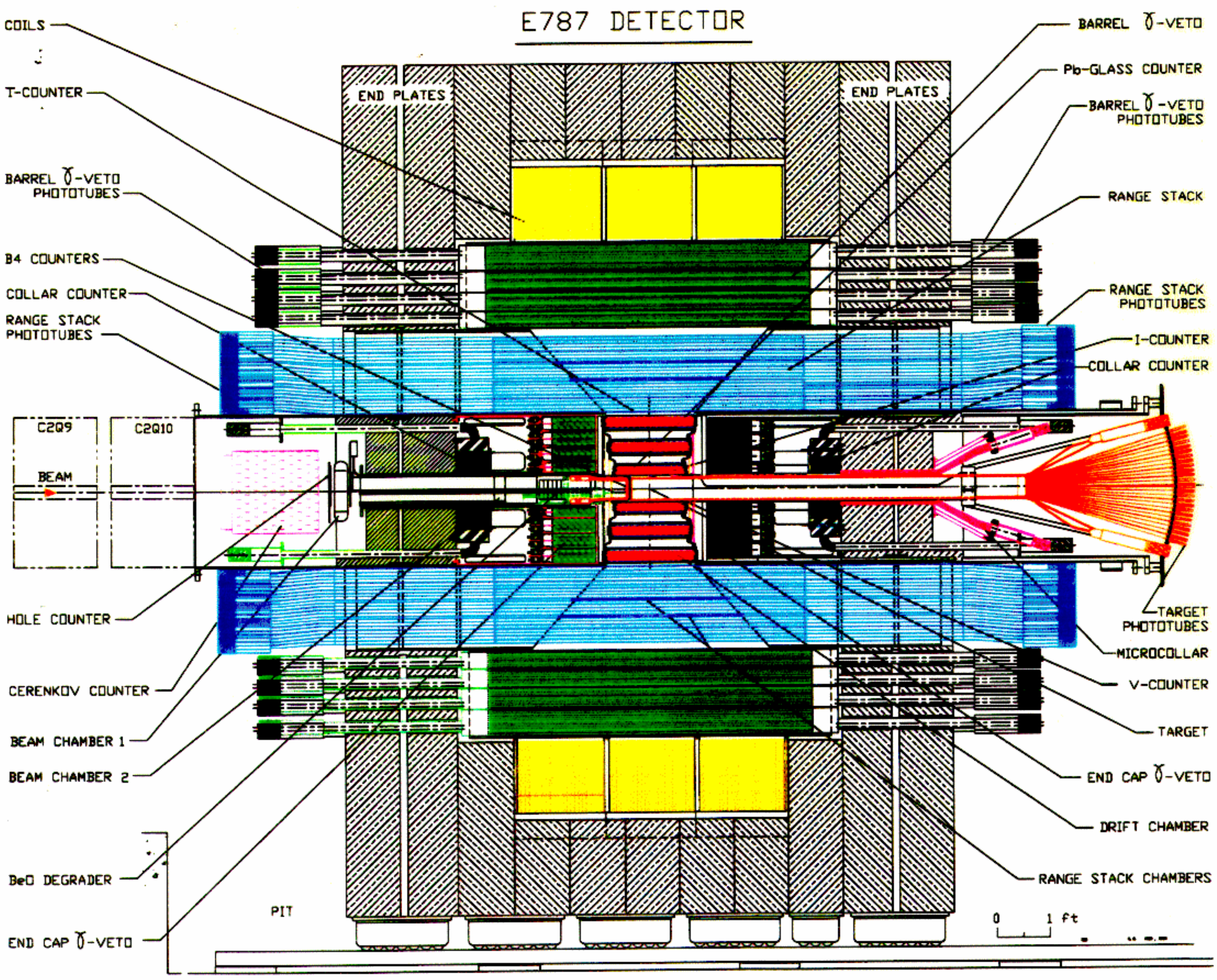
[6] Hindmarsh and Moulatsiotis, hep-ph/9807363

E787 strategy



- Work in kaon rest frame ⇒ stopped kaon beam (BeO degrader, scintillating fiber stopping target)
- Search in the high-momentum region ($p_\pi > 211$ MeV/c)
- Stop the decay pion in scintillator
  - Redundant measurements of track kinematics: energy and range
  - π/μ separation
    - Observe $\pi^+ \to \mu^+ \to e^+$ decay sequence ⇒ high-speed digitizers (2ns samples, 7μs depth)
    - dE/dx separation in scintillator
- π momentum measurement ⇒ low-mass tracking ($\Delta P/P \sim 0.9\%$ at 205 MeV/c)

- Photon veto
  - 4π coverage
  - Good timing, low thresholds
  - Time windows $\sim$ few ns; energy thresholds $\sim$ 0.2 - 3 MeV
  - CsI, Pb-scint, Pb-tile, Pb glass
- Beam instrumentation
  - K/π separation (Cerenkov counter, lucite radiator)
  - Fine spatial segmentation, tracking, good timing
    - Scintillating fiber (5mm square fiber) kaon stopping target
    - MWPC's (1.27 mm wire spacing)
- Rate capability
  - 4-5 MHz of K^+
  - 500 MHz digitizers in barrel, endcap, target, beam hodoscopes
- Minimize inactive material (undetected energy loss)

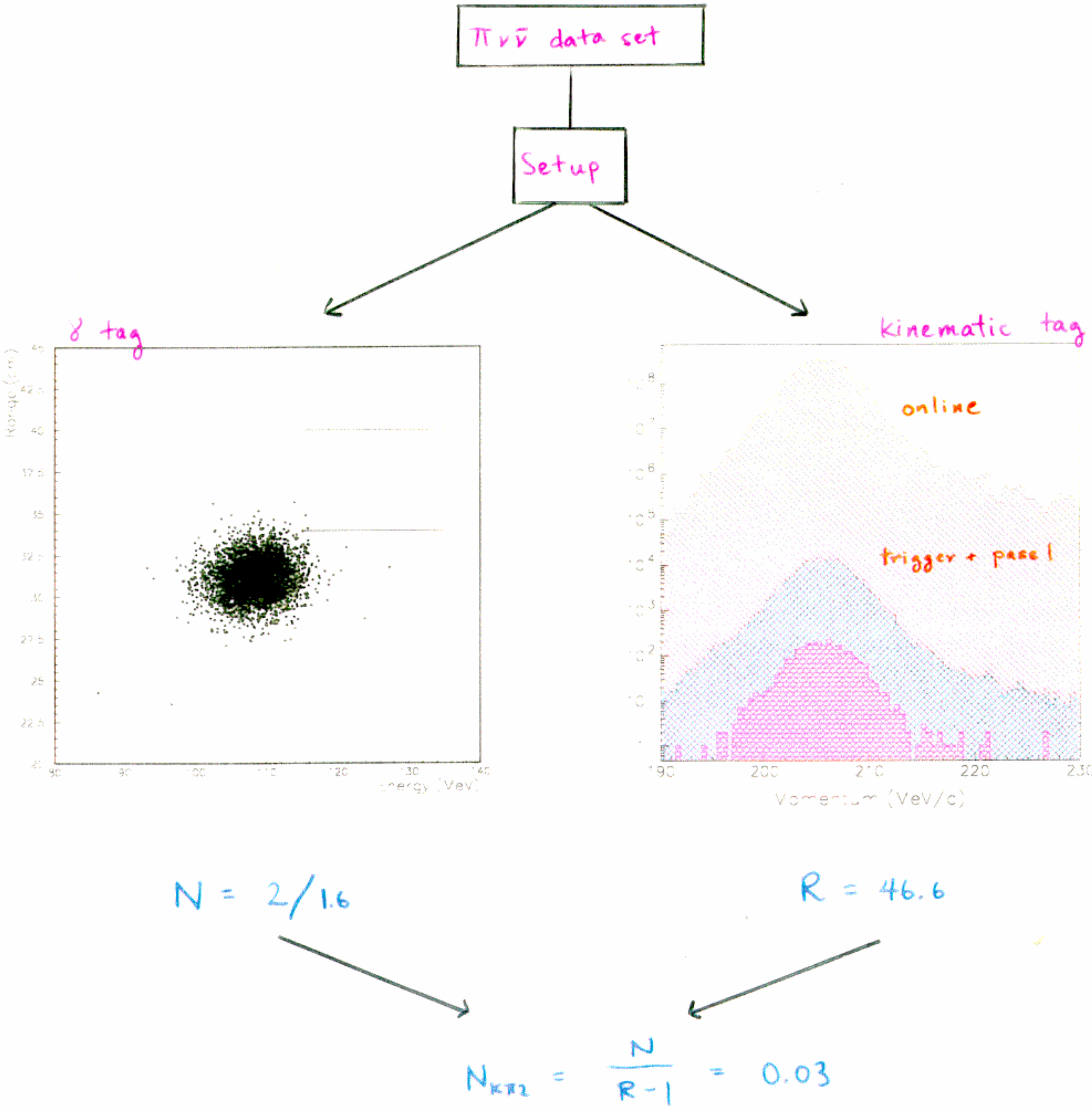


E787 DETECTOR
COILS
T-COUNTER
BARREL γ-VETO PHOTOTUBES
B4 COUNTERS
COLLAR COUNTER
RANGE STACK PHOTOTUBES
C2Q9
C2Q10
BEAM
HOLE COUNTER
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
BeO DEGRADER
END CAP γ-VETO
PIT
END PLATES
END PLATES
BARREL γ-VETO
Pb-GLASS COUNTER
BARREL γ-VETO PHOTOTUBES
RANGE STACK
RANGE STACK PHOTOTUBES
I-COUNTER
COLLAR COUNTER
TARGET PHOTOTUBES
MICROCOLLAR
V-COUNTER
TARGET
END CAP γ-VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0 1 ft

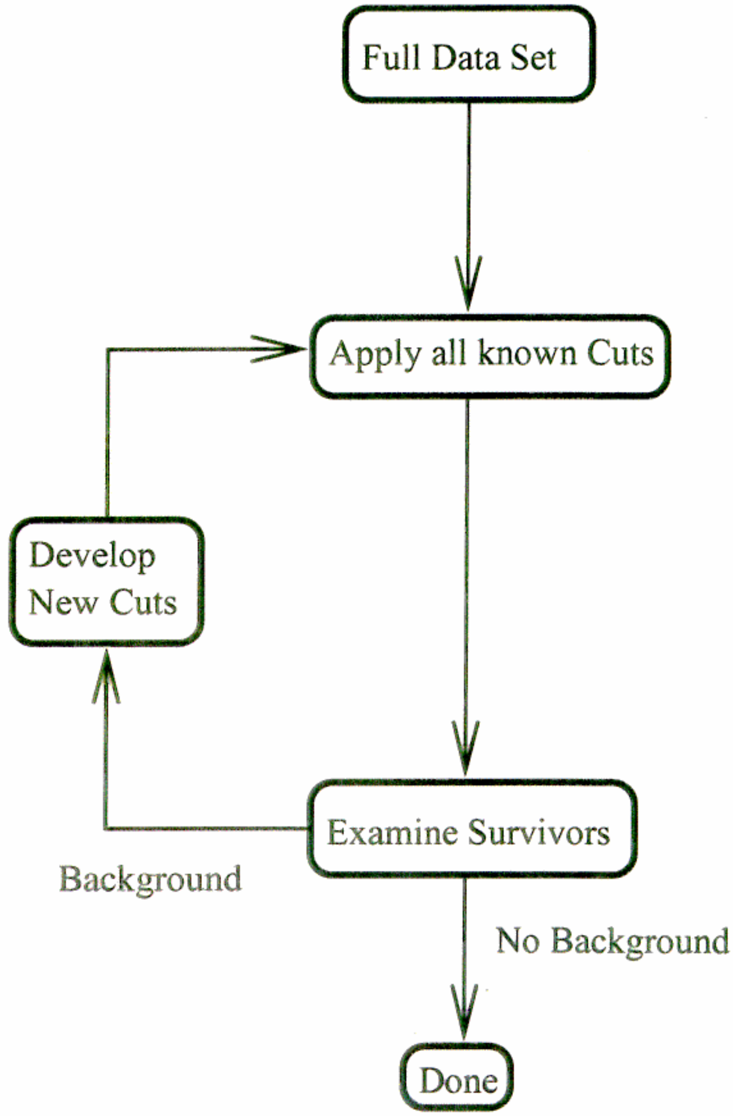
Offline analysis

- Blind analysis
  - Signal region is hidden (by inverting cuts) while cuts are developed and background levels estimated
- "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 levels in the signal region at the $10^{-3} - 10^{-2}$ event level
- Correlation studies
- Prediction of background levels around signal region (followed by confirmation)
- Background likelihood analysis (using predetermined likelihood functions) in the signal region for assessing candidate events.

$K^+ \to \pi^+\pi^0$ background



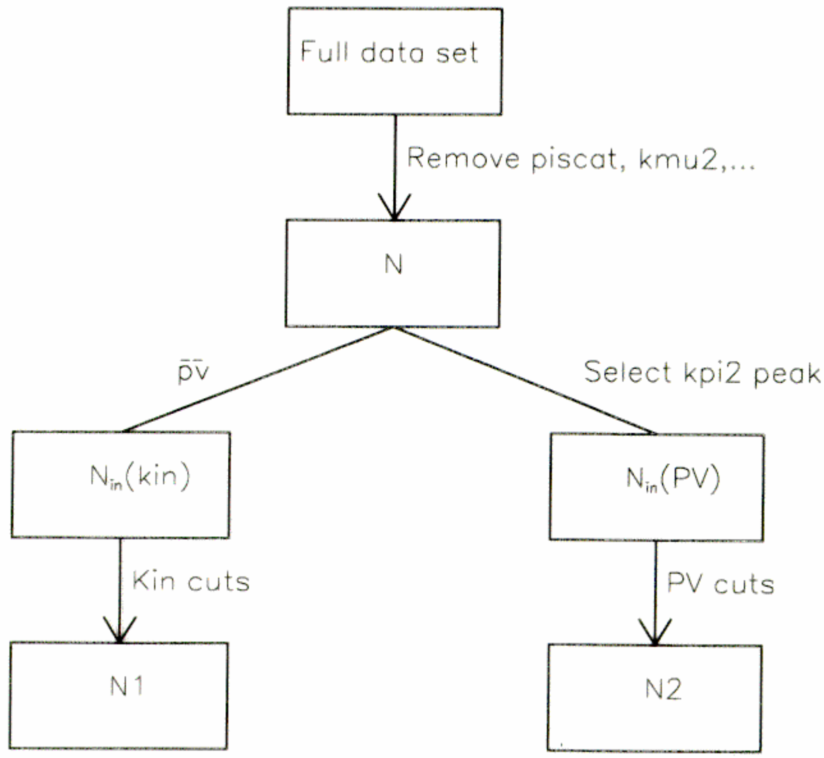
"Traditional" (non-blind) upper-limit approach



Easy to eliminate a signal.

Background estimation

Take $K^+ \rightarrow \pi^+\pi^0$ as an example:



$$R_{PV} = N2/N_{in}(PV)$$

$$N_{bg} = N1/(R_{PV}-1)$$

Background levels, 1995 dataset

Background	# events in signal region
$K_{\pi 2}$	0.03 ± 0.02
$K_{\mu 2}$	0.02 ± 0.02
Single beam	0.012 ± 0.009
Double beam	0.007 ± 0.007
CEX	0.01 ± 0.01
Total background	0.08 ± 0.03

Prediction of background level in the region just outside the signal region.

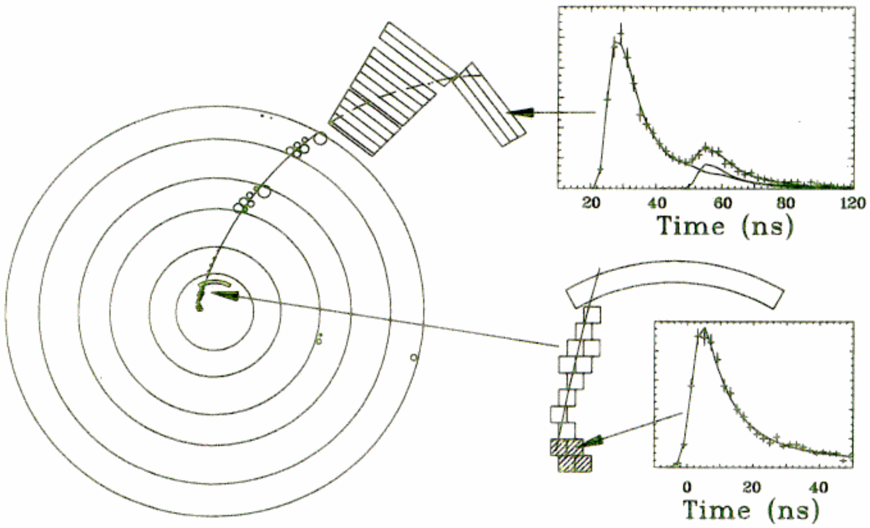
- Simultaneously loosen the two independent cuts for each background (tests correlations)
- Loosen all background types uniformly

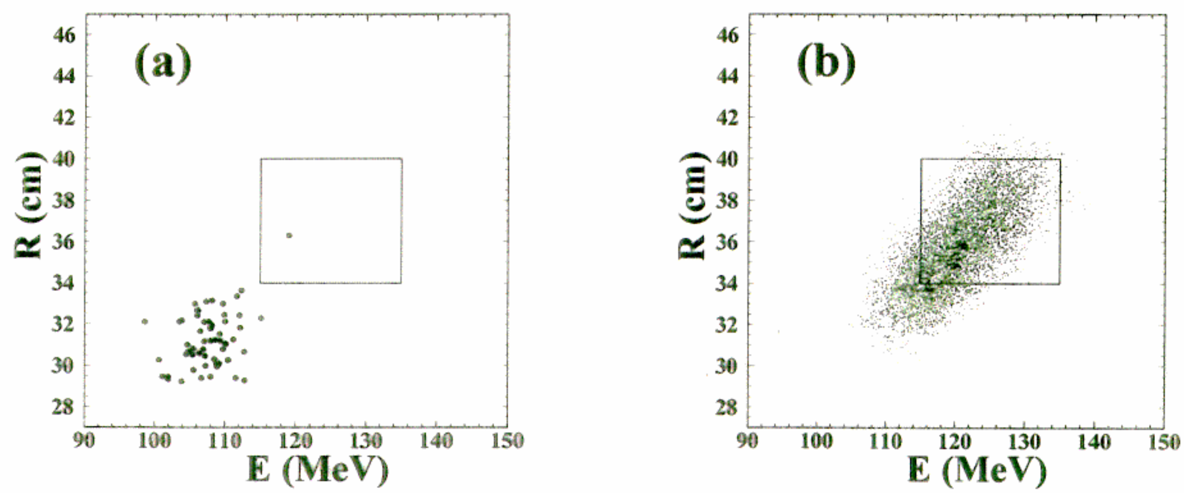
Bkg factor	Expected no. bkg	Observed no. bkg
$\times 10$	0.8 ± 0.3	0
$\times 20$	1.6 ± 0.7	2
$\times 150$	12 ± 5	15

- Good agreement between expected and observed background levels
- All 15 events in the $\times 150$ region are consistent with known backgrounds.
- Individual background types are consistent with expected levels.

Background	Expected no. bkg	Observed no. bkg
$K^+ \to \mu^+ \nu_\mu$	3.0	5
$K^+ \to \pi^+ \pi^0$	4.5	5
Single beam	1.8	2
Double beam	1.1	1
CEX	1.2	2 ± 1

One candidate event (1995 dataset)





The event is located at a point where the background likelihood is lower by a factor of 10 (0.008 ± 0.005 events) and the signal likelihood (relative acceptance) is 0.55.

$K^+ \rightarrow \pi^+ \nu \overline{\nu}$ and related results from 1995 data

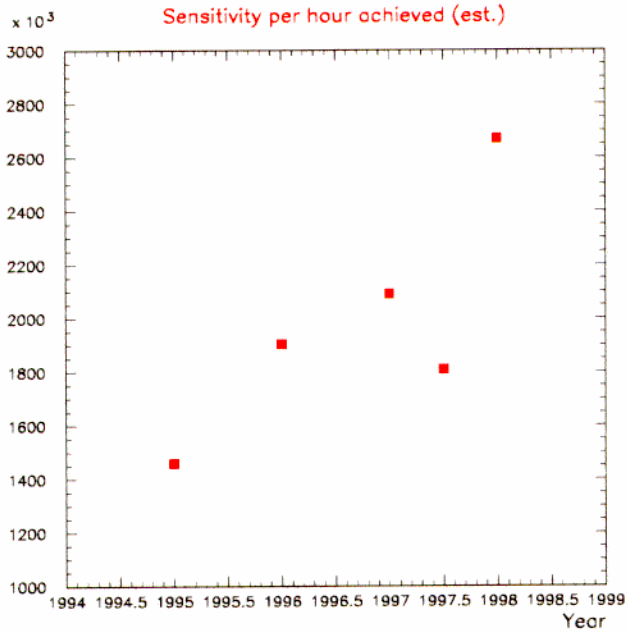
- Based on one event observed:

$$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu \overline{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$$

$$0.006 < |V_{td}| < 0.06$$

- Based on no events observed in $K^+ \rightarrow \pi^+ X^0$ region:

$$\mathrm{BR}(K^+ \rightarrow \pi^+ X^0) < 3.0 \times 10^{-10} \quad \text{(90\% CL, } \mathrm{M}_{\mathrm{X}^0}=0\text{)}$$



- 1996
  - Lower K^+ momentum $\Rightarrow$ higher K stopping fraction, lower accidental loss (but, requires more protons to maintain K flux)
  - Higher acceptance in trigger
- 1997
  - Further lowered K^+ momentum
  - Lower deadtime from trigger improvements
  - Higher acceptance from increased TD depth
- 1998 (ongoing)
  - Improved duty factor
  - Higher proton intensity on K production target
  - Optimization of running conditions (protons on target, K momentum, spill length)
  - Overall AGS proton intensity still below levels achieved in the past $\Rightarrow$ reasonable to expect further increase in sensitivity/hr by factor $\sim 1.3 - 1.5$.

Offline analysis

Goals

- Increase rejection to maintain signal/noise as sensitivity grows
- Maintain (or possibly even increase) acceptance at the same time

$K_{\pi 2}$

- Tracking improvements in range stack and target ⇒ better range resolution (core) and smaller tail
- Optimize combination of photon veto vs kinematic cuts (potentially could allow going to higher instantaneous rates)

$K_{\mu 2}$

- Tracking improvements in drift chamber ⇒ smaller momentum tail
- Range stack dE/dx likelihood analysis ⇒ effective against interacting muons
- Optimized $\pi^+ \to \mu^+ \to e^+$ analysis
- Optimized combination with kinematic cuts

1 beam

- New cuts with redundancy against tails in timing

2 beam

- Bkg relatively low
- Transient digitizer analysis?
- Extra beam wire chamber segmentation (1998) will help

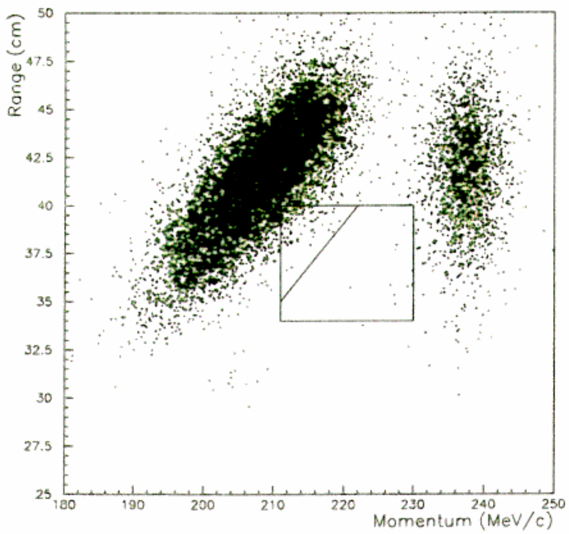
CEX

- Discriminant function analysis in target and beam hodoscopes

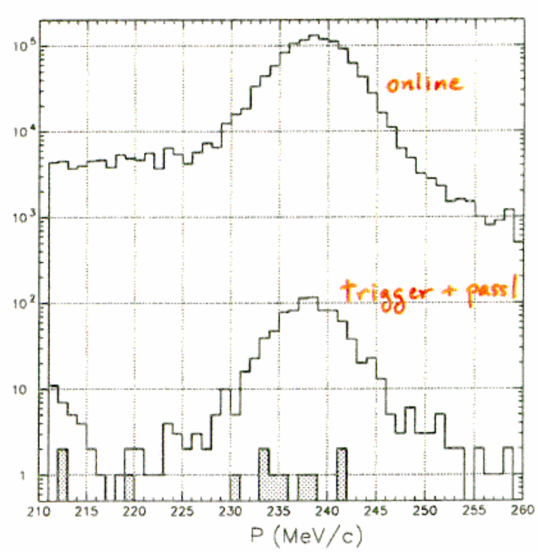
Background studies are advanced, looks promising

$K^+ \rightarrow \mu^+ \nu_\mu$ background

fail $\pi \rightarrow \mu \rightarrow e$



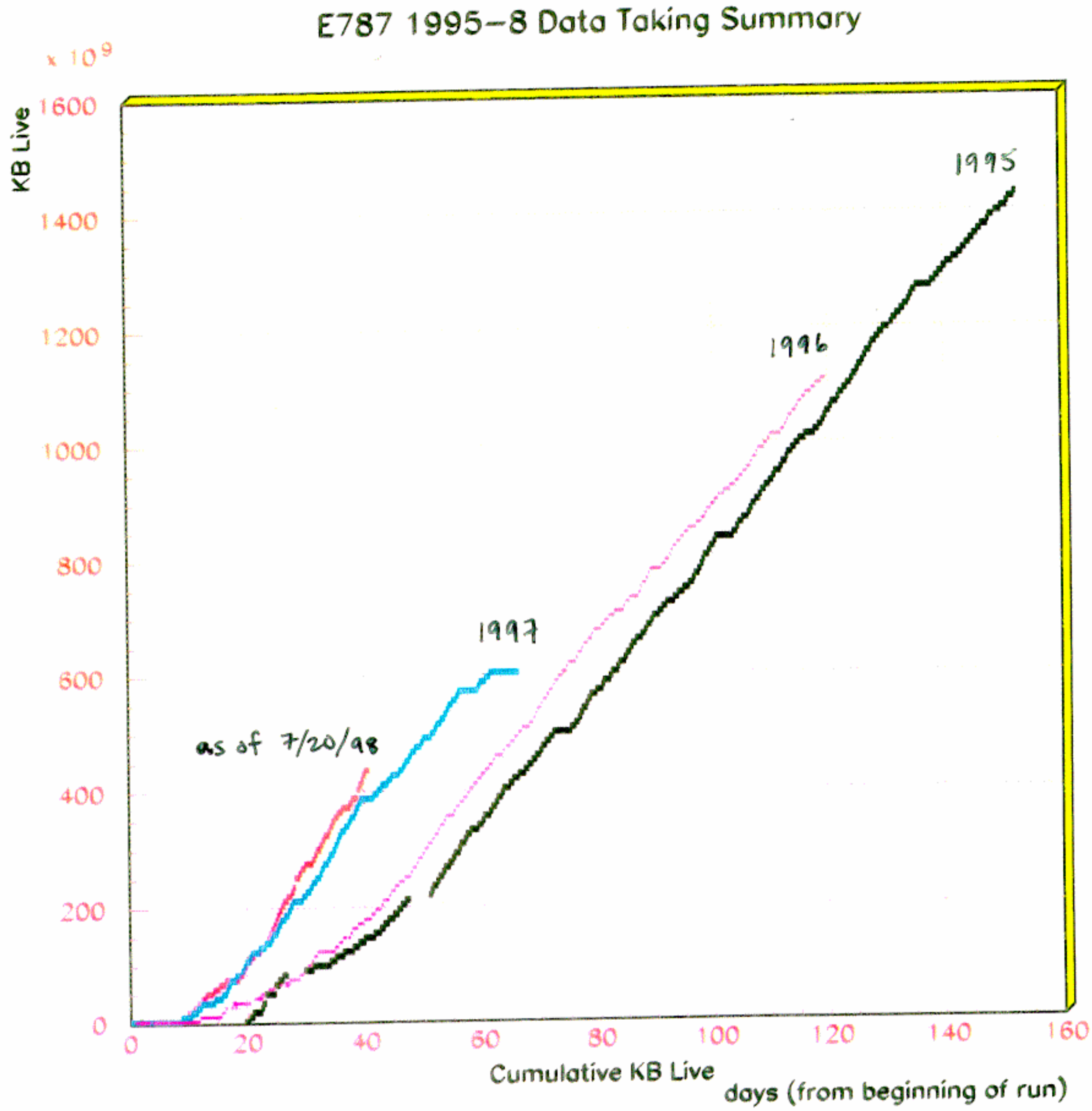
kinematic μ tag



$N = 24$

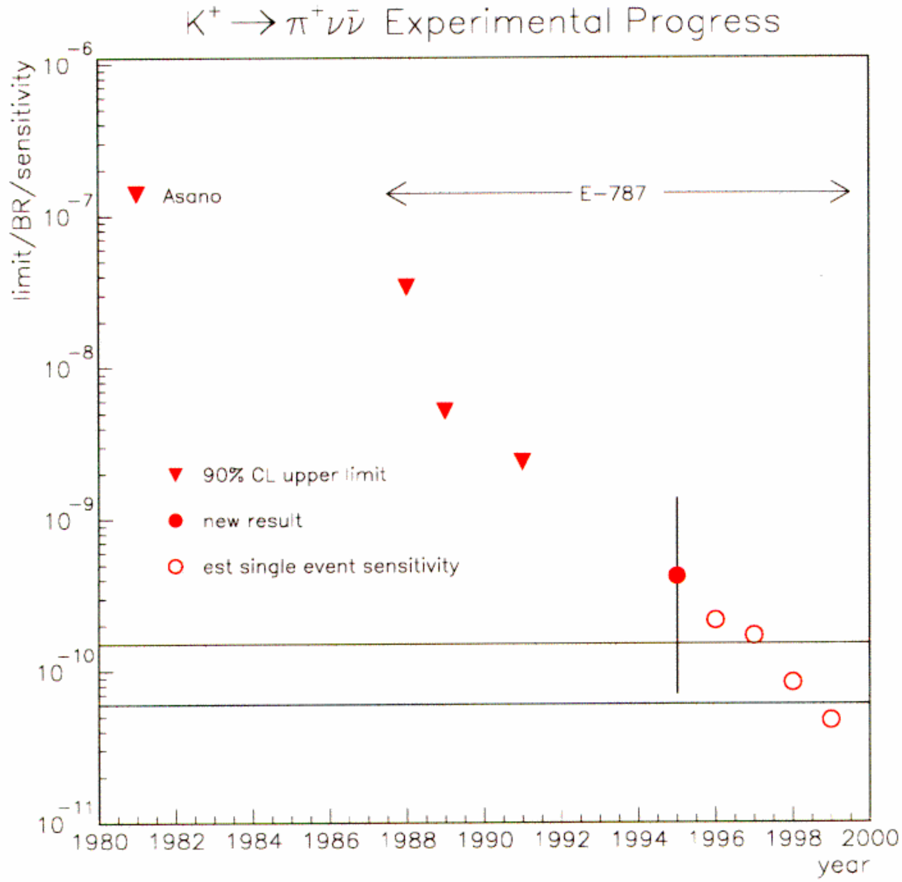
$R(\pi \rightarrow \mu \rightarrow e) = 1000$

$$N_{K\mu 2} = \frac{N}{R-1} = 0.024$$



27 week run anticipated in 1998

Prospects



- 1998: long run (ongoing) with $\times 2 \sim 3$ sensitivity/hr wrt 1995. 1999 extension?
- E787 detector has the power to suppress backgrounds to $K^+ \to \pi^+ \nu\overline{\nu}$ at the SM level, without slaughtering acceptance.
- Near term: analysis of 95-97 dataset should clarify whether one event observed so far was a statistical fluctuation.
- Medium term: exploration at the few event level of $K^+ \to \pi^+ \nu\overline{\nu}$ at the SM level.
- Longer term: further exploration of $K^+ \to \pi^+ \nu\overline{\nu}$ (BR to $< 20\%$) may be possible during the RHIC era with minimal or modest upgrades.