Sensitivity studies for a new $K^+ \to \pi^+ \nu \bar{\nu}$ experiment at FNAL

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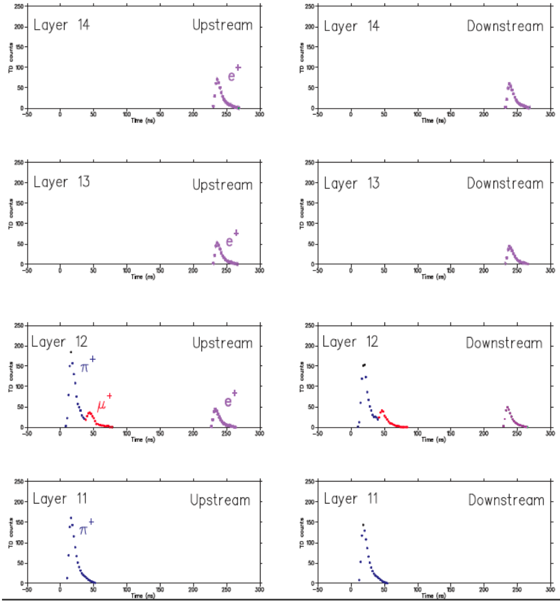
Acceptance improvements with respect to E949

Component	Factor
$\pi \rightarrow \mu \rightarrow e$	2.40 ± 0.07
Deadtimeless DAQ	1.35
Rate-dependence	1.19
Longer drift chamber	1.38
Higher B field	1.1
Range stack segmentation	1.2
Photon veto	1.3
Improved target	1.1
Macro-efficiency	1.18
Product	11.9

I will describe the justification for each factor in the following, usually by citing E949 publications, technical notes or theses.

$\pi \to \mu \to e$ detection in E949



$\pi \longrightarrow \mu \longrightarrow e$ acceptance factors

Positive identification of π^+ achieved by identification of $\pi \rightarrow \mu$ decay in range stack (RS) counter where π^+ stops and subsequent detection of $\mu \rightarrow e$ in stopping counter and neighboring counters.

Quantity	Acceptance	Comment
π decay	0.8912	$(3, \infty)$ ns
μ decay	0.990	$(0.02, \infty)$ μs
μ escape	0.98	E949 Technote K036
e^+ detection	0.97 ± 0.03	Guess [1]
Product	0.84 ± 0.03	
E949 acceptance	0.35	T.Sekiguchi thesis & K074.v1
Improvement factor	2.40 ± 0.07	

Lower time limit for pion decay driven by ability to resolve 3.0 MeV energy deposit of μ^+.

μ escape takes in account acceptance loss due to μ exitting stopping counter without depositing sufficient energy (1 MeV) for detection.

[1] Could quantify with MC

Detector improvements and $\pi \to \mu \to e$ acceptance

1. Waveform digitizer, ADC and multihit TDC on every RS channel (WFD 4x multiplex in E949)
2. Increased RS scintillator light yield
   - E949 Technote K014 shows that increasing the PE/MeV from 8 to 18 would increase the $\pi \to \mu \to e$ acceptance by $\times 1.39$ while maintaining the same background rejection.
3. Increased segmentation of RS (1.9cm thick in E949)
   - Reduced accidental veto loss (both for μ^+ and e^+)
   - Improved discrimination of π and μ

Deadtime-less DAQ and trigger

The average E949 livetime was 74% (PRD**77**, 052003 (2008)), so a deadtime-less DAQ and trigger would increase acceptance by $1/0.74 = 1.35$.

A deadtime-less DAQ and trigger would likely be necessary to achieve the $\pi \to \mu \to e$ acceptance improvement described in the previous slides as rudimentary $\pi \to \mu$ identification was an essential component of the $K^+ \to \pi^+ \nu \bar{\nu}$ trigger in E787/E949.

Rate dependence

E949 typically ran with $1.6 \times 10^6\ K^+/\mathrm{s}$ entering the target. This rate was approximately twice the anticipated rate due to the unavailability of the Siemens motor generator.
The acceptance gain expected due to running at half the E949 instantaneous intensity estimated from studies.

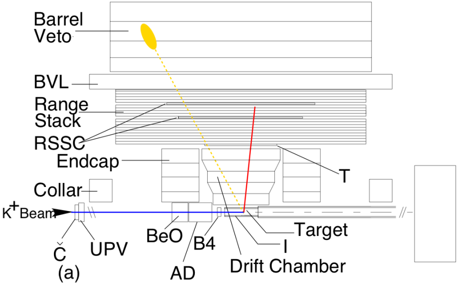
Component	Relative acceptance	Comment
Photon veto (pnn1)	1.045	Figure 12 of E949 K034
Photon veto (pnn2)	1.227	Ilektra Christidi's measurement
Drift chamber tracking	1.040	Benji Lewis's measurements
$\pi \rightarrow \mu \rightarrow e$ trigger	1.049	Benji Lewis's measurements
$\pi \rightarrow \mu \rightarrow e$ offline	1.07 ± 0.03	Section 3.5.4 of E949 K034
Beam/target cuts	1.092	Benji Lewis's measurements
Product (pnn1)	1.33 ± 0.04	
Product (pnn2)	1.56 ± 0.04	
Product (pnn1)	**1.19**	Excluding $\pi \rightarrow \mu \rightarrow e$ components
Product (pnn2)	1.39	Excluding $\pi \rightarrow \mu \rightarrow e$ components

pnn1 and pnn2 refer to signal regions above and below the $K_{\pi 2}$ peak, resp.

Longer drift chamber

The E949 drift chamber was 50.8 cm long at the outer radius of 43.3 cm (PRD**77**, 052003 (2008)).
Increasing the length to 80 cm and decreasing the radius to 41 cm would increase the solid angle acceptance by 1.38.

Lengthening the drift chamber would require lengthening the RS and the barrel photon veto, too.



Higher B field

The E949 magnet provided a 1 T solenoidal field (PRD**77**, 052003 (2008)). Increasing the field to 1.25 T is estimated to give an increase in acceptance of 1.1 based on the $\times 1.12$ increase in acceptance due to improved energy resolution in E949 compared to E787. Simulation is needed to confirm this estimate.

Experiment	$\sigma(E)$ (MeV)
E787	3.205 ± 0.005
E949	2.976 ± 0.005

Measured energy resolution for $K_{\pi 2}$ events (E949 K-034).

Improved RS monitoring in E949 enabled rate-dependent gain corrections to be applied to each PMT in the RS and lead to the improved energy resolution.

Greater RS segmentation

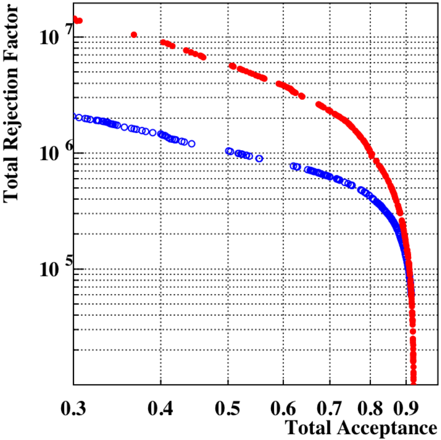
In E949 the RS consisted of 1.902 cm thick counters in 24 azimuthal sectors. The width of the inner- and outermost RS counters was 11.8 and 22.0 cm, resp. Increasing the RS segmentation, both radially and azimuthally, would lead to

1. Improved resolution in the range measurement
2. No need for RS straw chambers
3. Lower accidental losses in $\pi \to \mu \to e$

The first item is estimated to give an increase in acceptance of $\times 1.1$ analogous to the increase estimated for the improvement in momentum resolution. Simulation is needed to confirm this estimate.
The second item would remove the need for cuts that reject events that exit the RS in $\pm z$ via the straw chambers. These cuts had an acceptance loss of 0.91 (E949 K-034), so the acceptance gain would be $\times 1.1$.
The acceptance gain for the last item was already assessed, so the net increase in acceptance is estimated to be $\times 1.2$.

Photon veto

The barrel photon veto was 15.3 X_0 in E787 and increased to 17.6 X_0 in E949 for normal incidence.



For the nominal acceptance of 0.80, the background rejection increased by $\times 2$. For fixed rejection, the acceptance increased by $\times 1.07$.

The estimated increase in acceptance for a 23 X_0 shashlyk-style barrel veto with improved instrumentation is $\times 1.3$.

Improved target

A target with higher light yield and improved instrumentation is guessed to provide an increase in acceptance of $\times 1.1$.

"Macro-efficiency" factors

"Macro-efficiency" factors for E949 running were assessed in E949 technote K025:

Efficiency	Component
0.858	AGS Beam on primary target
0.890	Data-taking enabled
	Sub-components of data-taking
0.939	DAQ functional
0.967	Tape(!) changes/pedestal runs
0.985	LESB III [2] functional

Assuming efficiencies of 0.95 for beam on primary target and data-taking, yields an acceptance increase of $\times 1.18$.

[2] Low-Energy Separated Beamline III

Summary

Based on E949 experience, improvements could yield an acceptance increase of > 10 for a stopped kaon experiment at FNAL.

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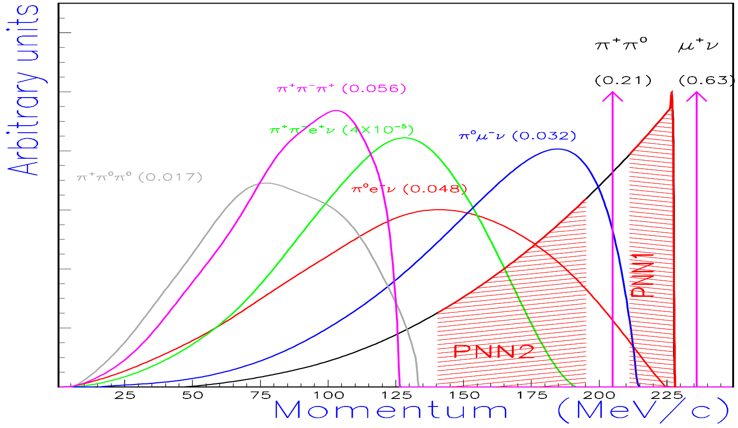
Simulation, additional analysis of E949 data and studies of prototypes are needed to fully justify some of these factors.

Extras

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



E949 detector