FERMILAB-SLIDES-09-002-PPD

Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay at Fermilab
Proposal P996

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representing the P996 Collaboration

Outline

E949 experimental method

Improvements for P996

- Detector acceptance
- Kaon production and transport

Sensitivity and backgrounds

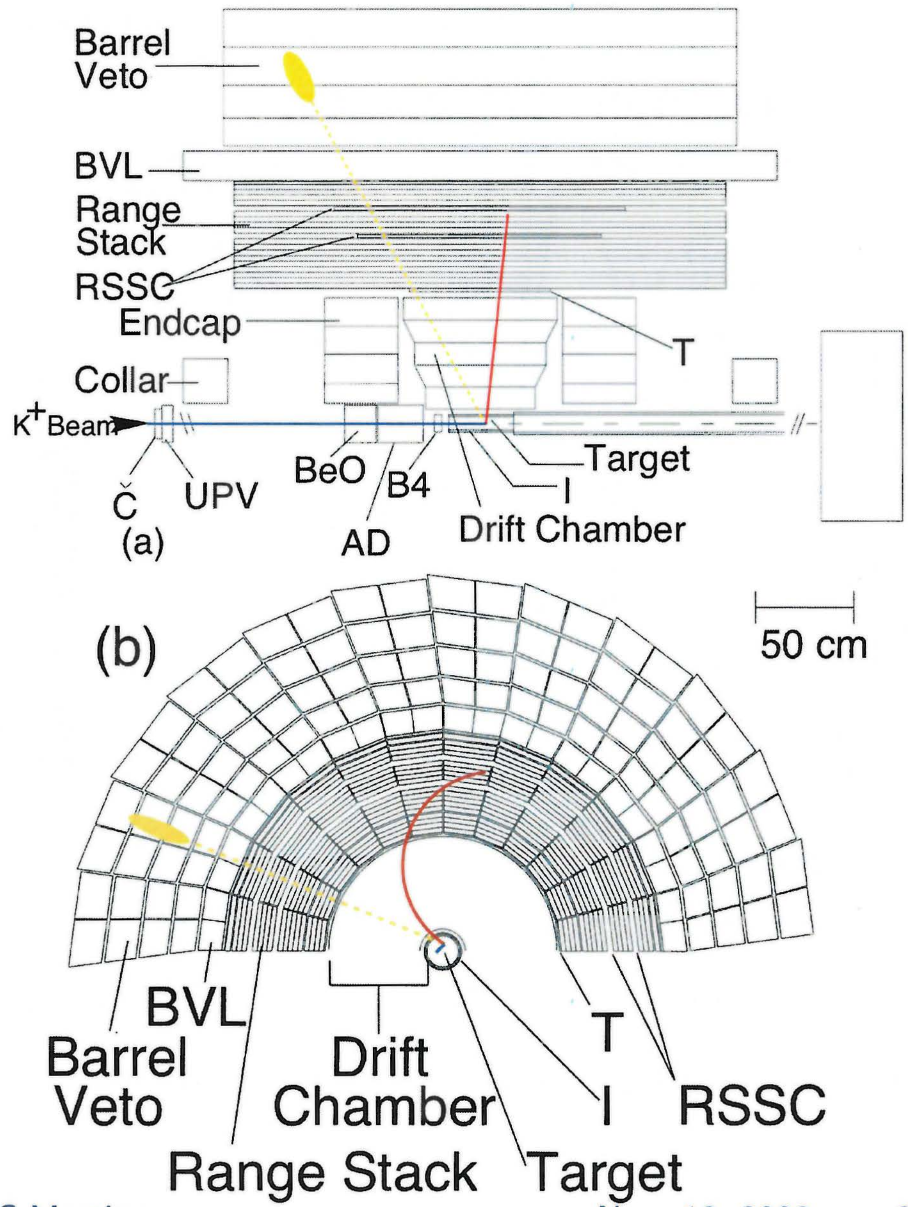
Cost and schedule

Conclusions

E949 Experimental Method

In the standard model, 85 of 1,000,000,000,000 K^+ decays are to $\pi^+\nu\bar{\nu}$.

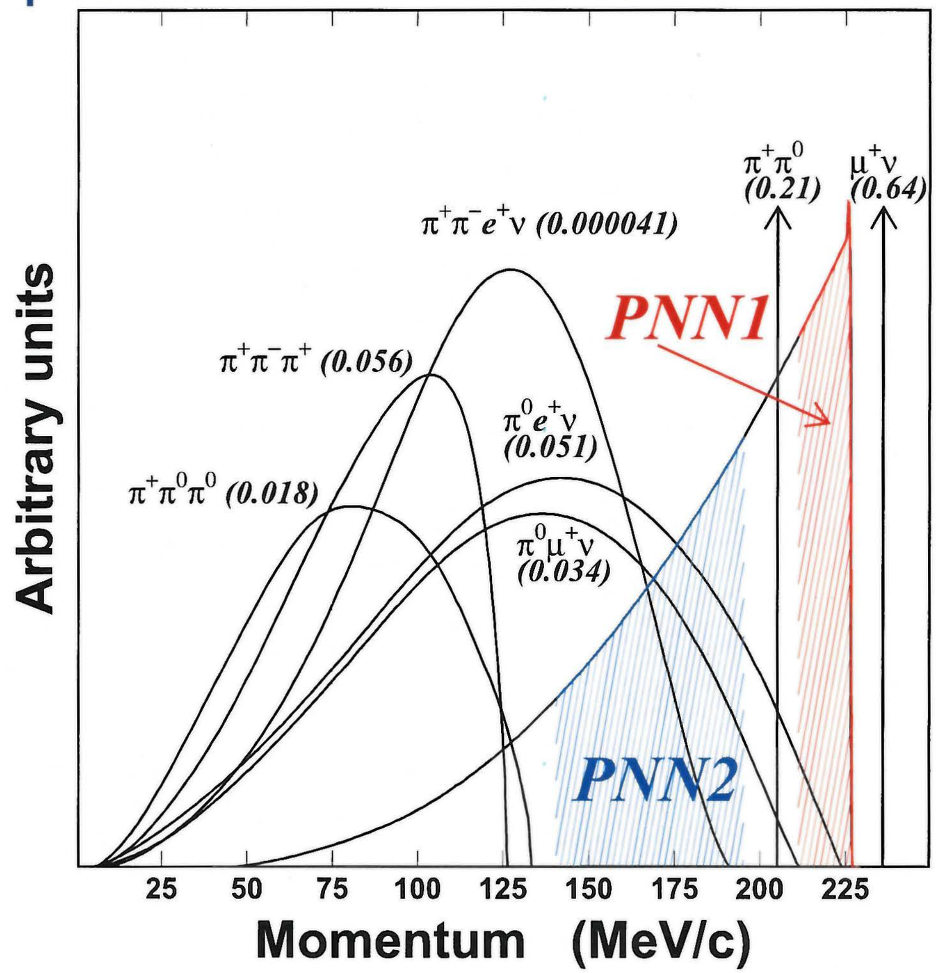
- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in range stack
- Veto photons, charged tracks



E949/E787 Background, Acceptance and Results

PNN1	E949	E787
Kaons	1.8×10^{12}	5.9×10^{12}
Bkgd evts	0.30 ± 0.03	0.14 ± 0.05
Acceptance	2.2×10^{-3}	2.0×10^{-3}
$N_{\rm obs}$	1	2
S/B	1.1	8, 59

PNN2	E949	E787
Kaons	1.7×10^{12}	1.7×10^{12}
Bkgd evts	$0.93 \pm^{0.36}_{0.29}$	1.22 ± 0.24
Acceptance	1.37×10^{-3}	0.84×10^{-3}
$N_{\rm obs}$	3	1
S/B	0.20, 0.42, 0.47	0.20



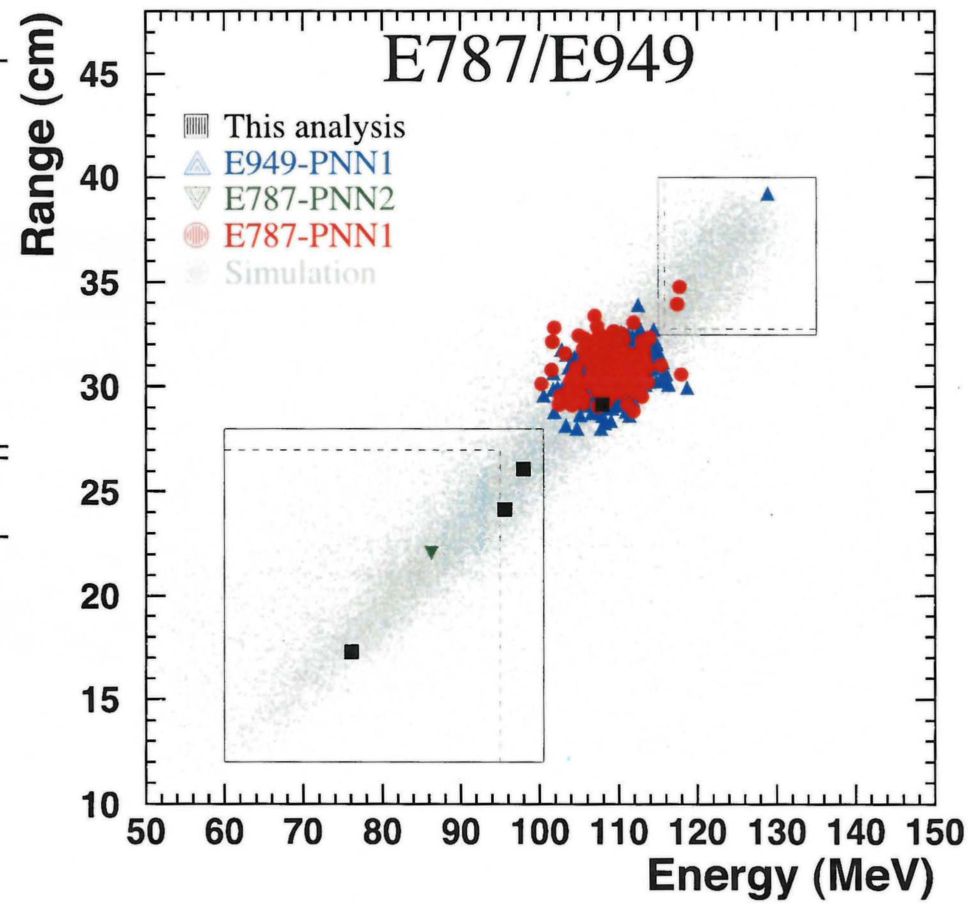
The probability of all observed candidates to be due to background is 0.001.

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ was evaluated with a likelihood method that takes into account the signal-to-background ratio S/B of the individual candidates.

E949/E787 Results

PNN1	E949	E787
Kaons	1.8×10^{12}	5.9×10^{12}
Bkgd evts	0.30 ± 0.03	0.14 ± 0.05
Acceptance	2.2×10^{-3}	2.0×10^{-3}
N_{obs}	1	2
S/B	1.1	8, 59

PNN2	E949	E787
Kaons	1.7×10^{12}	1.7×10^{12}
Bkgd evts	$0.93 \pm ^{0.36}_{0.29}$	1.22 ± 0.24
Acceptance	1.37×10^{-3}	0.84×10^{-3}
N_{obs}	3	1
S/B	0.20, 0.42, 0.47	0.20



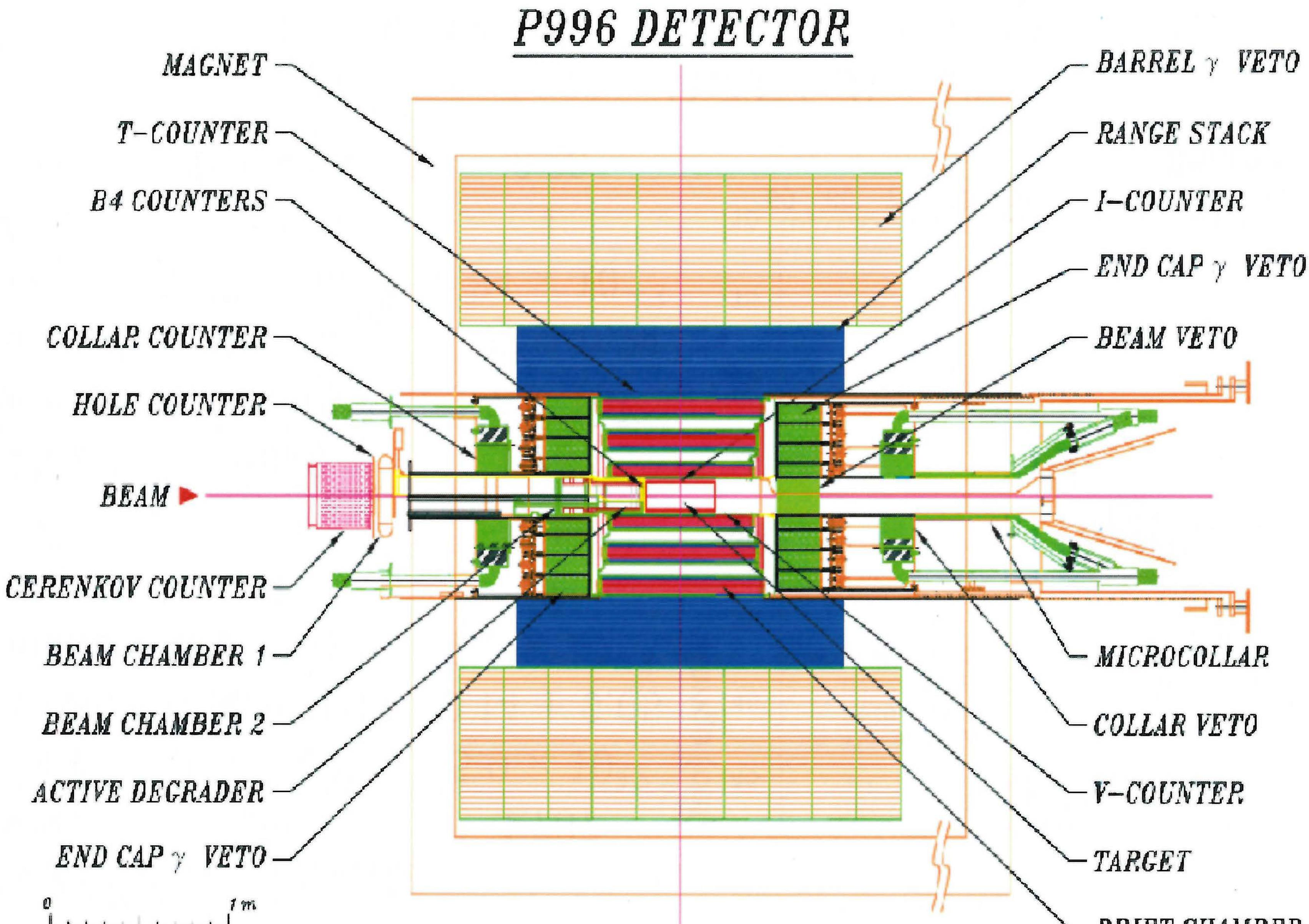
$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Standard model $(0.85 \pm 0.07) \times 10^{-10}$

$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ was evaluated with a likelihood method that takes into account the signal-to-background ratio S/B of the individual candidates.

P996 Detector

Use existing (CDF or CLEO) solenoid



Detector Acceptance

P996 detector improvements will enable increases in signal acceptance. Expected increases are based largely on E949/E787 data and measurements.

Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	$11.28^{+3.25}_{-2.22}$

Additional acceptance gains expected from trigger improvements are not yet quantified.

$\pi \longrightarrow \mu \longrightarrow e$ Acceptance Factors

1. Identify range stack counter where π^+ stops
2. Detect $\pi \rightarrow \mu$ decay in stopping counter
3. Detect $\mu \rightarrow e$ in stopping counter and neighboring counters

Quantity	Acceptance	Range
π decay	0.8734	(3,105) ns
μ decay	0.9450	(0.1,10) μs
μ escape	0.98	
e^+ detection	0.97 ± 0.03	
Product	0.78 ± 0.02	
E949 acceptance	0.35	
Improvement factor	2.24 ± 0.07	

Detector Improvements and $\pi \rightarrow \mu \rightarrow e$ Acceptance

1. Eliminate 4x multiplexing of range stack (RS) waveform digitizers used in E949.
   - Reduced loss due to accidentals
2. E949 RS: 19 layers (1.9cm thick), 24 azimuthal sectors.
   P996 RS: 30 layers (0.95cm thick), 48 sectors.
   - Reduced accidental veto loss (μ^+ and e^+)
   - Improved discrimination of π and μ
3. Increased RS scintillator light yield by higher QE photodetectors and/or better optical coupling.
   - Improved μ identification
4. Deadtime-less DAQ and trigger: $\pi \rightarrow \mu \rightarrow e$ acceptance improvements; rudimentary $\pi \rightarrow \mu$ identification was an essential component of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ trigger in E787/E949.

Livetime and Delayed-Coincidence Acceptance

Livetime	
E949 livetime	0.74
P996 estimate	1.00
Acceptance increase	1.35

Macro-efficiency	
E949 average	0.76
E949 best week	0.84
MiniBooNE (FY08)	0.85
P996 estimate	0.85 ± 0.05
Acceptance increase	1.11 ± 0.07

E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds.

Delayed coincidence	
E949 acceptance	0.763
P996 estimate	0.851 ± 0.035
Acceptance increase	1.11 ± 0.05

Improved Momentum and Range Resolution and Increased Solid Angle

P996/E949 momentum resolution	0.90	Increase B from 1 T
Acceptance increase	1.12 ± 0.05	to 1.25 T
P996/E949 range resolution	0.87 ± 0.05	More finely segmented
Acceptance increase	1.12 ± 0.06	range stack
E949/E787 energy resolution	0.93	Improved calibration
Acceptance increase	1.12	

Solid angle increase

	Drift chamber	Range Stack	Barrel veto	Lengths
E949	50.8	180	190	cm
P996	84.7	250	350	cm
Acceptance increase	1.38			

Photon Veto and Target Improvements

Photon veto	
E949	17.3 radiation lengths
P996	23.0 radiation lengths
Acceptance increase	$1.65^{+0.39}_{-0.18}$

Estimated increase taken from simulated KOPIO PV performance.
KOPIO simulation was adjusted to agree with E949 PV efficiency.

Target	
E949	3.1 m long, single-end readout
P996	1.0 m long, double-end readout
Acceptance increase	1.06 ± 0.06

Rate of Incident Kaons

The expected rate of kaons incident on P996:

$$
\begin{aligned}
N_K(\mathrm{P996})/\mathrm{spill} &= N_K(\mathrm{E949})/\mathrm{spill} \times R_{\mathrm{surv}} \times R_{\mathrm{proton}} \times R_{K/p} \\
&= 12.8 \times 10^6 \times 1.1048 \times 1.48 \times (6.8 \pm 1.7) \\
&= (142 \pm 36) \times 10^6.
\end{aligned}
$$

- $R_{\mathrm{surv}} = 1.1048$, the relative rate of survival of 550 MeV/c kaons in the 13.74m P996 K^+ beamline compared to 710 MeV/c K^+ in the 19.6m E949 beamline,
- $R_{\mathrm{proton}} = (96 \times 10^{12})/(65 \times 10^{12})$ protons per spill,
- $R_{K/p} = 6.8 \pm 1.7$, the relative production rate of K^+ into the P996 and E949 kaon beamline acceptance as determined from MARS-LAQSGM simulation.

Rate of Stopped Kaons

For one year of running (5000 hours=18×10^6 s), the total number of stopped kaons in the experimental target is

$$\begin{aligned} N_{\mathrm{Kstop}}/\mathrm{year} &= N_K(\mathrm{P996})/\mathrm{spill}/(t_{spill} + t_{inter}) \times 5000 \text{ hours} \times f_{\mathrm{stop}} \\ &= (142 \pm 36) \times 10^6/27.33\mathrm{s} \times 18 \times 10^6 \times (0.60 \pm 0.13) \\ &= (5.6 \pm 1.9) \times 10^{13}. \end{aligned}$$

- $t_{spill} = 25.67$s spill,
- $t_{inter} = 1.67$s interspill with the stretcher,
- $f_{\mathrm{stop}} = 0.60 \pm 0.13$, K^+ stopping fraction estimated with FLUKA-based simulation. The same simulation estimated a 27% stopping fraction for E949 compared to the measured 21% stopping fraction.

	E949	P996	
Instantaneous Rate (K^+, π^+)	8.4	7.6	MHz

$K^+ \to \pi^+ \nu \bar{\nu}$ Events per Year

The number of signal events per 5000-hour year is

$$\begin{aligned} N_{K^+ \to \pi^+ \nu \bar{\nu}} &= \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \times N_{\mathrm{Kstop}} \times A_{\mathrm{E949}} \times R_{\mathrm{acc}} \\ &= (0.85 \pm 0.07) \times 10^{-10} \times (5.6 \pm 1.9) \times 10^{13} \\ &\quad \times (3.59 \pm 0.36) \times 10^{-3} \times (11.3^{+3.3}_{-2.3}) \\ &= 194^{+89}_{-79} \end{aligned}$$

where

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$
- $A_{\mathrm{E949}} = (2.22 \pm 0.17) \times 10^{-3} + (1.37 \pm 0.14) \times 10^{-3}$
  $= \mathrm{PNN1} + \mathrm{PNN2}$ acceptance
- $R_{\mathrm{acc}} = (11.3^{+3.3}_{-2.3})$, the product of acceptance factors gained over E949.

Summary of Improvement Factors

Ratio P996/E949	
$11.3^{+3.3}_{-2.3}$	Detector acceptance
6.3 ± 2.1	Stopped kaons per hour
5.3	Hours per year

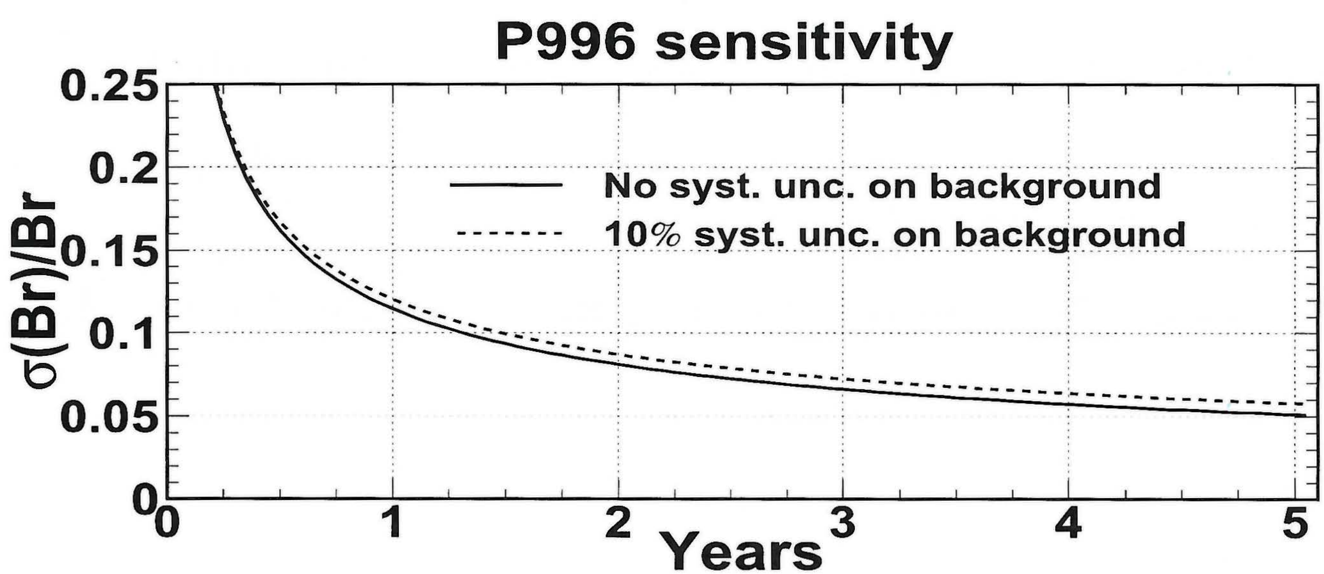
Stopped kaon yield $\equiv R_{\rm prot} \times R_{K/p} \times R_{\rm surv} \times R_{\rm stop}/R_{\rm spill}$
where

- $R_{\rm proton}$ is the ratio of protons per spill,
- $R_{K/p}$ is the relative production rate of K^+ into the P996 and E949 kaon beamline acceptance.
- $R_{\rm surv}$ is the relative K^+ survival rate in the kaon beamline,
- $R_{\rm stop}$ is the relative K^+ stopping fractions, and
- $R_{\rm spill}$ is the relative spill length.

Comparable K^+, π^+ instantaneous rate in E949 (8.4 MHz) and P996 (7.6 MHz).

Sensitivity and Backgrounds

- Background sources in P996: same as E949.
  - Kaon production at 150 GeV may introduce accidental hits in P996; however, E787 and E949 observed no evidence for background or accidental activity due to the primary beam.
- Sensitivity estimate assumption:
  - Signal-to-background (S/B) ratio PNN1 and PNN2 subregions is the same as E949 and remains constant as signal acceptance increased.



Sensitivity

- Under simple assumptions, the fractional precision of the measured $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ is comparable to the projected theoretical uncertainty of 6%.
- E949 has demonstrated that a likelihood-based technique can improve the sensitivity by taking into account the variation in S/B in the signal region.
- Extensive methodology to determine the background rates and signal acceptance from data was developed and refined by E949/E787. This methodology provides the basis for suppressing systematic uncertainties and enabling precise measurement of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$.

Preliminary Total Project Cost Estimate (FY10 $M)

WBS element	Description	Total Cost	60% conting.	Total w/cont.
1.0	**Total Project Cost**	**33.3**	**20.0**	**53.3**
1.1	Accelerator and Beams	7.5	4.5	12.0
1.2	Detector	22.4	13.4	35.8
1.3	Project Management	2.7	1.6	4.4
1.4	Other Project Cost	0.7	0.4	1.1

- Based on E949 experience or Fermilab FY99 fixed target operations.
- Includes use of an existing solenoid.
- More work is needed after mature designs have been made.

Projected Timescale

Milestone/Activity	**Time Period**
Stage One Approval	Fall 2009
DOE Approval of Mission Need (CD-0)	Spring 2010
Approve Alt. Selection/Cost Range (CD-1)	Fall 2010
Baseline Review (CD-2)	End of 2011
Start Construction (CD-3)	Spring 2012
Begin Installation	Mid-2013
First Beam/Beam Tests	End of 2013
Complete Installation	Mid-2014
First Data (CD-4)	End of 2014

Stage-1 approval is necessary to build a strong collaboration, make progress on the design, compete with NA62 (run start mid-2012) and use the Tevatron in stretcher mode.

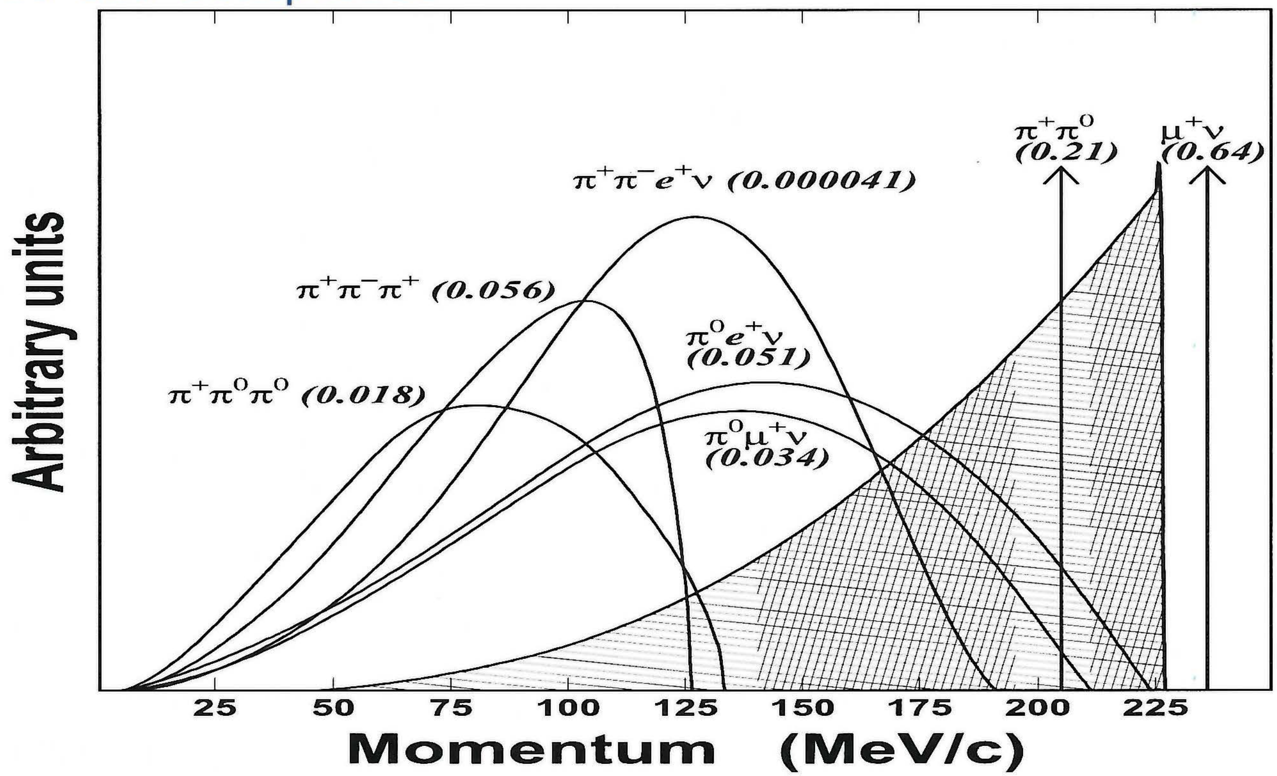
Conclusions

- The Standard Model prediction for $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ is theoretically robust at the 5% level.
- $K \to \pi\nu\bar{\nu}$ offers unique sensitivity to probe essentially all models of new physics that couple to quarks within the reach of the LHC.
- Based on the experience and demonstrated performance of BNL E949, a precise and timely measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ is possible using 10% of the Main Injector protons and the Fermilab Tevatron as a Stretcher.
- Stage-1 approval is necessary to
  1. Build a strong collaboration,
  2. Make progress on the design,
  3. Compete with NA62 (run start mid-2012) and
  4. Use the Tevatron in stretcher mode.

Extras

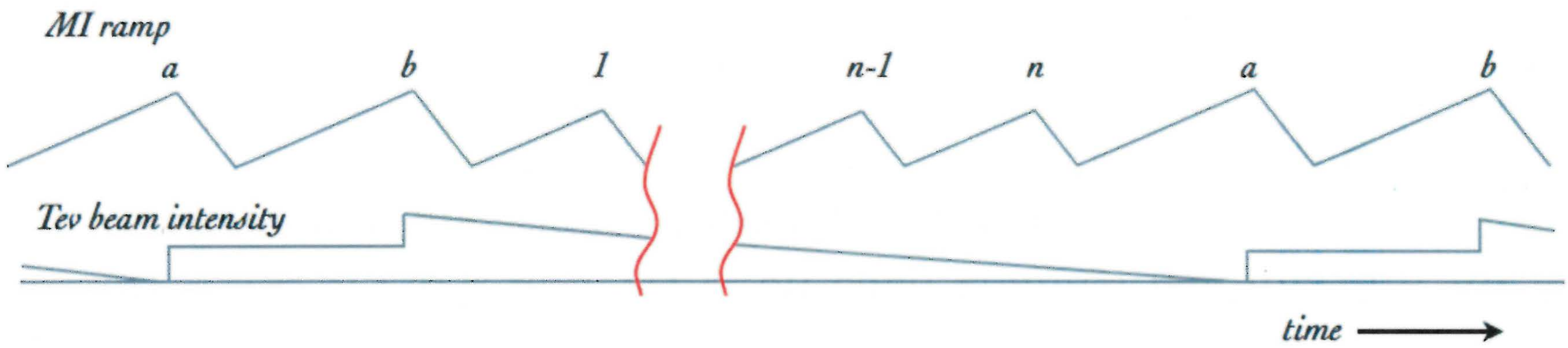
Component	E949'	P996	Ratio
Proton mom. (GeV/c)	21.5	150	
Protons/spill	65×10^{12}	96×10^{12}	$R_{\text{proton}} = 1.48$
Spill length(s)	2.2	25.67	
Interspill(s)	3.2	1.67	
Duty factor	0.41	0.94	
protons/sec(ave.)	12×10^{12}	3.6×10^{12}	
protons/sec(inst.)	15.9×10^{12}	3.8×10^{12}	
Kaon mom. (MeV/c)	710	550	
K beamline length(m)	19.6	13.74	
Eff. beam length(m)	17.6	13.21	
K survival factor	0.0372	0.0411	$R_{\text{surv}} = 1.1048$
Ang. acc. (msr)	12	20	$R_{\text{ang}} = 1.66$
$\Delta p/p(\%)$	4.0	6.0	$R_{\Delta p} = 1.5$
K^+:π^+ ratio	3	2.63 ± 0.33	
Relative K/proton	—	—	$R_{K/p} = 6.8 \pm 1.7$
N_K/spill	12.8×10^6	$(142 \pm 36) \times 10^6$	
T_{eff}/spill (s)	2.0		
N_K/sec(inst.)	6.3×10^6	$(5.5 \pm 1.4) \times 10^6$	
$N_{K+\pi}$/sec(inst.)	8.4×10^6	7.6×10^6	
N_K/sec(ave.)	2.6×10^6	$(5.2 \pm 1.3) \times 10^6$	
Stopping fraction	0.21	0.60 ± 0.13	
Kstop/s(ave.)	0.69×10^6	$(3.1 \pm 1.0) \times 10^6$	
Running time(hr)	—	5000	
Kstop/"year"	—	$(5.6 \pm 1.9) \times 10^{13}$	

E949 background and acceptance



Background	PNN2	PNN1 Standard	PNN1 Extended
$K_{\pi2(\gamma)}$	$0.695\pm^{0.164}_{0.180}$	0.019 ± 0.004	0.216 ± 0.023
Muon	0.011 ± 0.011	0.015 ± 0.002	0.068 ± 0.011
K_{e4}	$0.176\pm^{0.244}_{0.143}$		
Beam	0.001 ± 0.001	0.007 ± 0.003	0.009 ± 0.003
CEX	$0.013\pm^{0.016}_{0.013}$	0.004 ± 0.001	0.005 ± 0.001
Total	$0.93\pm^{0.36}_{0.29}$	0.05 ± 0.01	0.30 ± 0.03
Acc.(10^{-3})	1.37 ± 0.14	1.69 ± 0.14	2.22 ± 0.17

Stretcher operation



The Main Injector is being upgraded for the NOνA program for which the 120-GeV cycle time will be $T_n = 1.333$ s. To reach 150 GeV, the cycle time would be approximately $T_k = 1.667$ s, assuming the maximum ramp rate of 240 GeV/s for NOνA operation.

Operating scenario in which the Main Injector delivers two 150-GeV beam pulses (a and b, with cycle times T_k) to the Tevatron followed by n pulses of 120-GeV beam to the neutrino program, with cycle time T_n. Slow spill can occur over the time period $nT_n + T_k$.

Front-end electronics and redundancy

- Front-end electronics for each photodetector-based readout will consist of a base and signal splitter that feeds a waveform digitizer (WFD), an ADC and a multihit TDC.
  - The WFD would be a 500-MHz, 10-bit ADC.
  - The ADC would be a lower frequency WFD with more dynamic range.
- Experience with E949/E787 has shown that the redundancy provided by a TDC, ADC and WFD on each channel is important for high photon veto and signal detection efficiency.

$\pi \longrightarrow \mu \longrightarrow e$ 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.

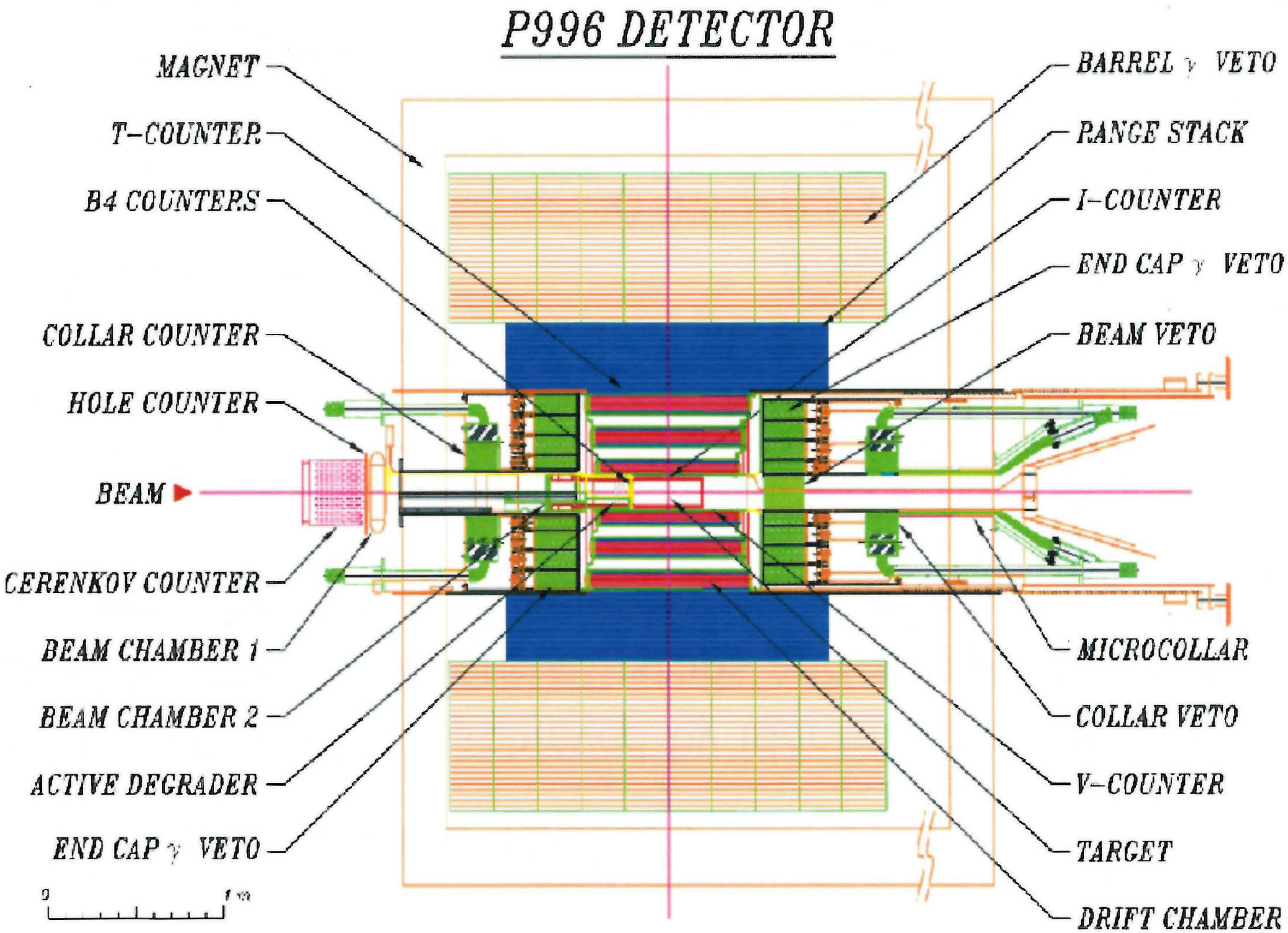
Quantity	Acceptance	Range
π decay	0.8734	(3,105) ns
μ decay	0.9450	(0.1,10) μs
μ escape	0.98	
e^+ detection	0.97 ± 0.03	
Product	0.78 ± 0.02	
E949 acceptance	0.35	
Improvement factor	2.24 ± 0.07	

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.

Solid Angle Increase

	Drift chamber	RS	Barrel veto	Lengths
E949	50.8	180	190	cm
P996	84.7	250	350	cm
Acceptance increase	1.38			



Livetime and delayed-coincidence acceptance

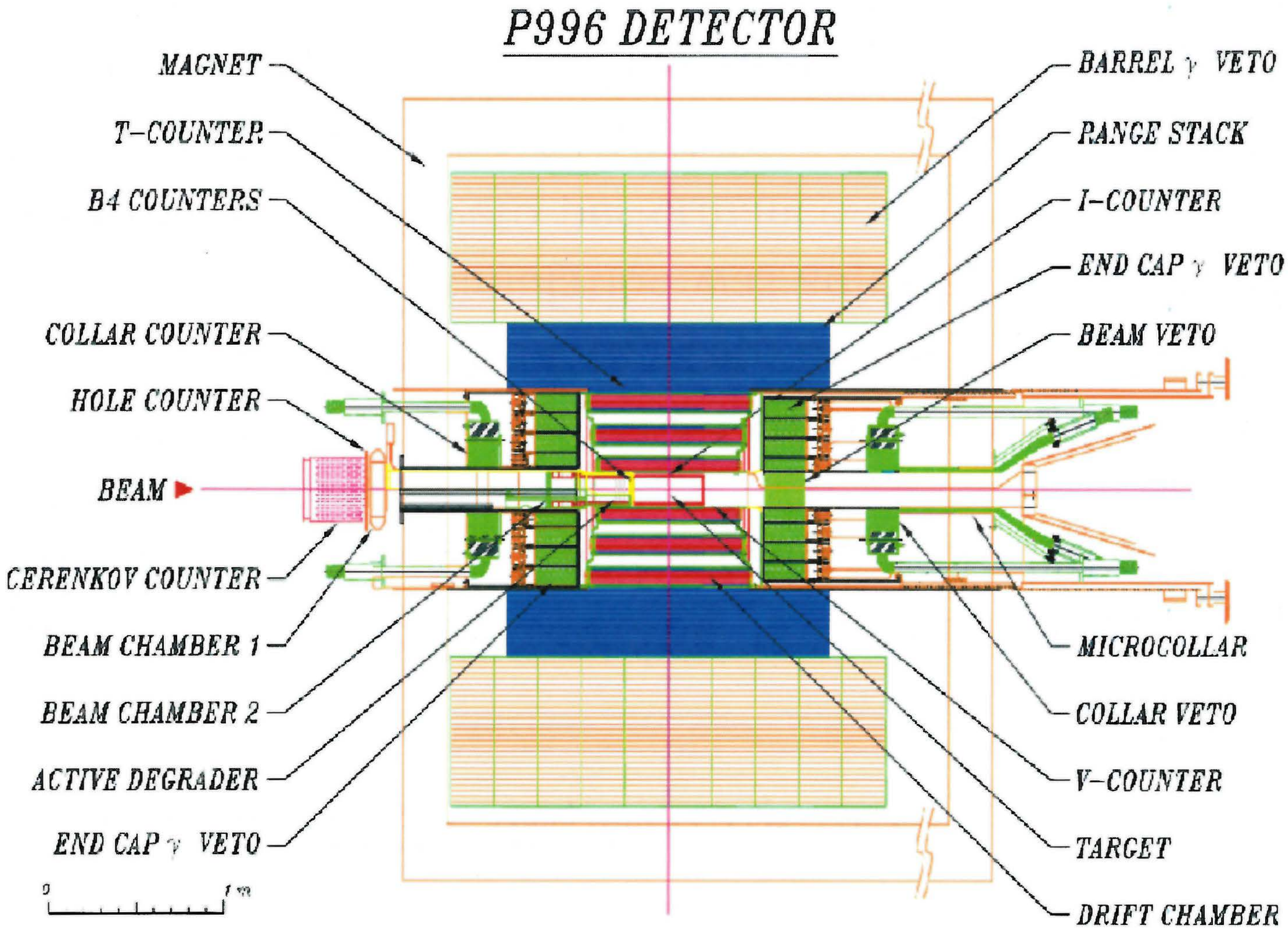
1. E949 had a typical deadtime of 26%. A deadtimeless DAQ and trigger would gain 1.35 in acceptance.
2. The "macro-efficiency" of the best week for E949 was 0.84 and is consistent with 2008 MiniBooNE and SciBooNE performance. An estimated P996 macro-efficiency of 0.85 ± 0.05 represents a factor of 1.11 ± 0.07 improvement compared to the E949 average of 0.76.
3. E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds. The overall online and offline acceptance of this requirement was 0.763 in E949. A deadtimeless DAQ and trigger are assumed to attain an acceptance of 0.851 ± 0.035 with a (2.0 ± 0.5) ns requirement for a gain of 1.11 ± 0.05.

Improved momentum and range resolution

1. Increasing the B-field from 1 T to 1.25 T improves the momentum resolution by 0.90. This improvement is estimated to increase the acceptance by 1.12 ± 0.05. (The energy resolution of E949 was improved by 0.93 compared to E787 and the acceptance increased by 1.12.)
2. A more finely segmented RS is estimated to improve the range resolution by 0.87 ± 0.05 which would give an acceptance increase of 1.12 ± 0.06.

Solid angle increase

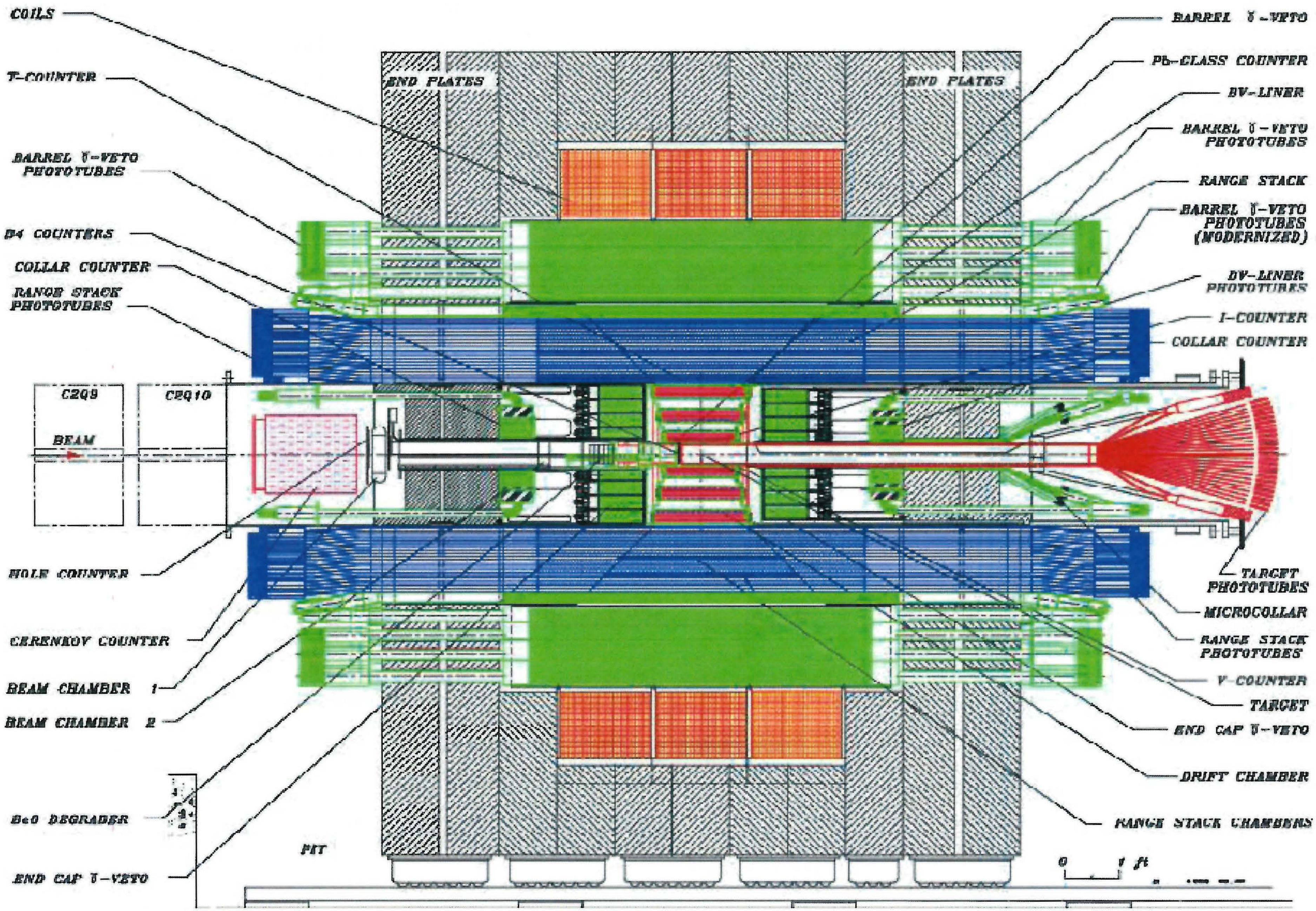
The E949 drift chamber was 50.8 cm long at the outer radius of 43.3 cm. A solid angle acceptance increase of 1.38 would be achieved by lengthening the drift chamber to 84.7 cm. This requires increasing the RS from 1.8m to $\sim$2.5 m and the barrel photon veto from 1.9m to $\sim$3.5 m.



Photon veto and target improvements

1. The barrel region of P996 would be 23 radiation lengths (rl) compared to 17.3 rl in E949 and is estimated to increase the acceptance by $1.65^{+0.39}_{-0.18}$.
   The estimate is based on simulation studies of the KOPIO ($K^0_L \to \pi^0 \nu \bar{\nu}$ experiment) photon veto of thicknesses of 16, 18, 21.6 and 26 rl. The KOPIO simulation was adjusted to agree with measured E949 photon veto performance.
2. The E949 scintillating target had 3.1m long, 5mm square fibers with single-ended readout. of each fiber. In P996, double-ended readout of a $\sim$1 m long target would increase the light yield and improve the measurement of the kaon decay point in the beam direction. The acceptance is estimated to increase by 1.06 ± 0.06.

E949 detector



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