Final results on $K^+ \to \pi^+ \nu \bar{\nu}$ from BNL E949

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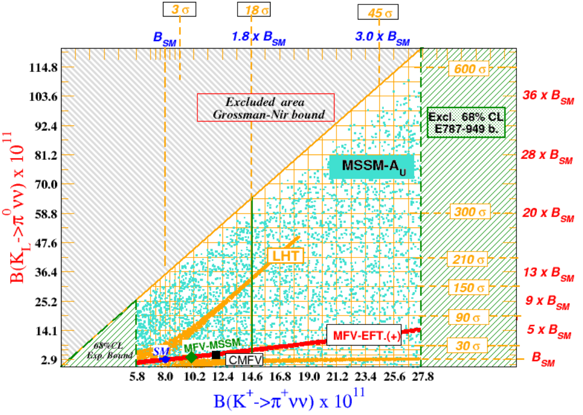
Sensitivity to New Physics

The $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio can be precisely predicted in the SM (and most models) owing to knowledge of the transition matrix element from similar processes and minimal long-distance effects.

In the SM, $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$ (arXiv:0805.4119).

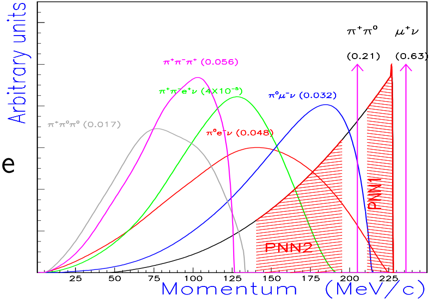


Ref: G.Isidori, arXiv:0801.3039, attributed to Frederico Mescia

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

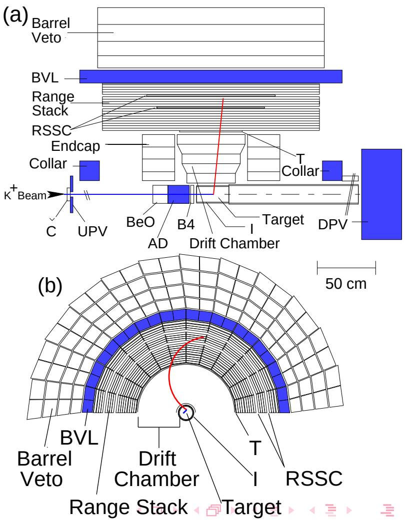
Region	**"PNN2"**	**"PNN1"**
$P(\pi^+)$ MeV/c	[140,195]	[211,229]
Stopped K^+	1.7×10^{12}	7.7×10^{12}
Background events	1.22 ± 0.24	0.45 ± 0.06
Candidate events	1	3
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	$< 22 \times 10^{-10}$ (90% CL)	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$
Reference	PRD**70**, 037102 (2004)	PRD**77**, 052003 (2008)
	E787	E787& E949

Rate *vs.*
π^+ momentum in K^+ rest frame



E949 experimental method

- **Measure everything possible**
- $\sim 700\ \mathrm{MeV}/c\ \mathrm{K}^+$ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum P in drift chamber
- Measure π^+ range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- New/upgraded detector elements compared to E787

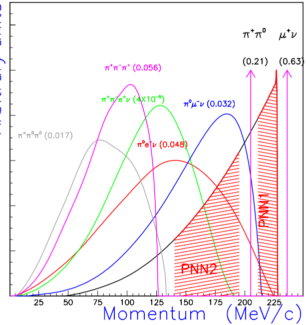


The Secret of Finding Rare Decays - J.Mildenberger (& J.Hart)

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background with at least two independent cuts.
- Measure background with data, if possible, by inverting cuts and measuring rejection taking any correlation into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- "Blind analysis". Don't examine signal region until all backgrounds verified.

Backgrounds in the pnn2 region



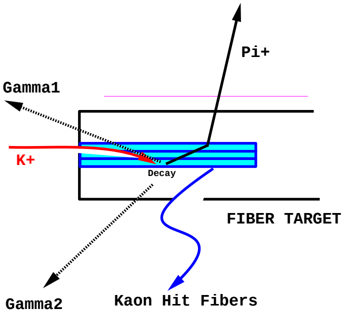
Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.8×10^{-10}
$K^+ \to \pi^+\pi^0$	$2092000000.0 \times 10^{-10}$
$K^+ \to \pi^+\pi^0\gamma$	$2750000.0 \times 10^{-10}$
$K^+ \to \pi^+\pi^- e^+\nu$	409000.0×10^{-10}
$K^+ \to \mu^+\nu$	$6344000000.0 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$62000000.0 \times 10^{-10}$
$K^+ \to \mu^+\pi^0\nu$	$332000000.0 \times 10^{-10}$
CEX	$\sim 46000.0 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.0 \times 10^{-10}$

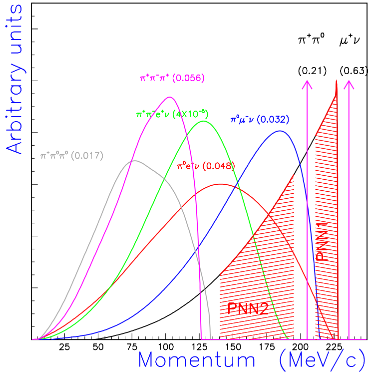
CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\mu^-\nu)$

$K^+ n \to K^0 X$ rate is empirically determined.

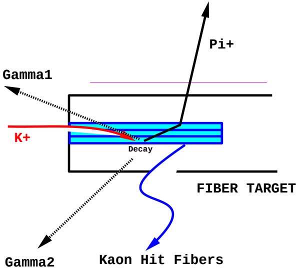
Main pnn2 background: $K^+ \to \pi^+\pi^0$ -scatters

The main background below the $K^+ \to \pi^+\pi^0$ peak is due to $K_{\pi 2}$ decays where the π^+ scatters in the target losing energy simultaneously obscuring the correlation with the π^0 direction.



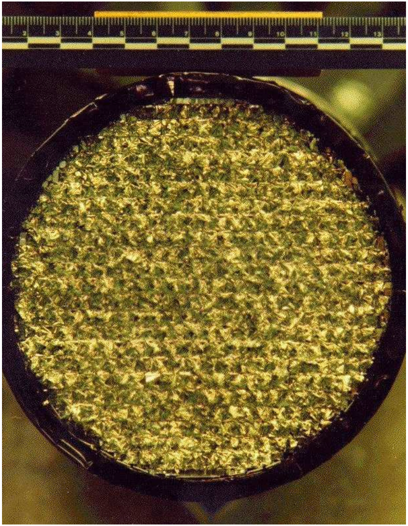


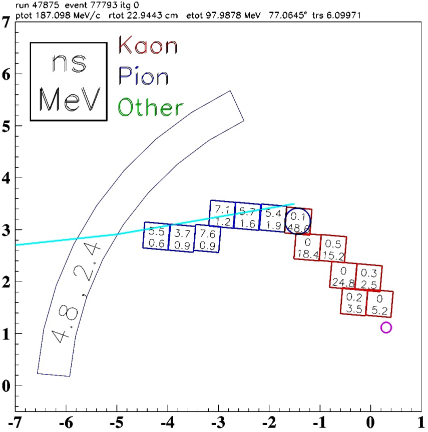
Suppression of $K_{\pi 2}$-scatter background



- Photon veto of $\pi^0 \rightarrow \gamma\gamma$
  Photon detection in beam region is important
- Identification of π^+ scattering in the target
  - kink in the pattern of target fibers
  - π^+ track that does not point back to the K^+ decay point
  - energy deposits inconsistent with an outgoing π^+
  - unexpected energy deposit in the fibers traversed by the K^+

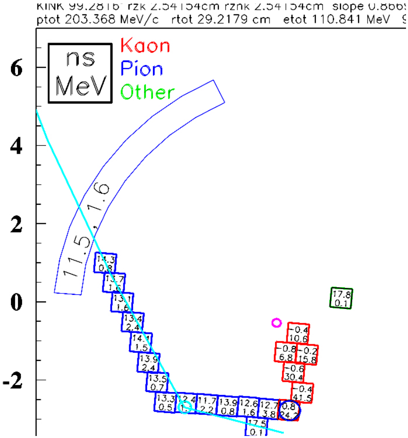
E949 scintillating fiber target



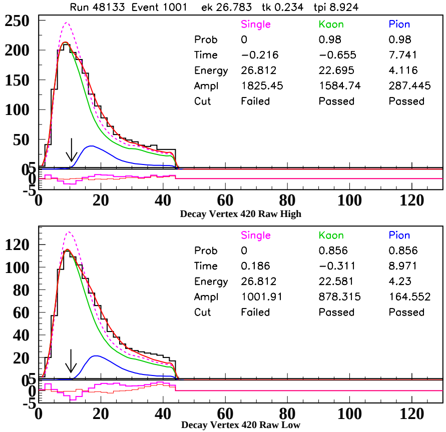


'Typical' pattern in target fibers for $K^+ \to \pi^+\pi^0$ decay.

Identification of π^+ scattering

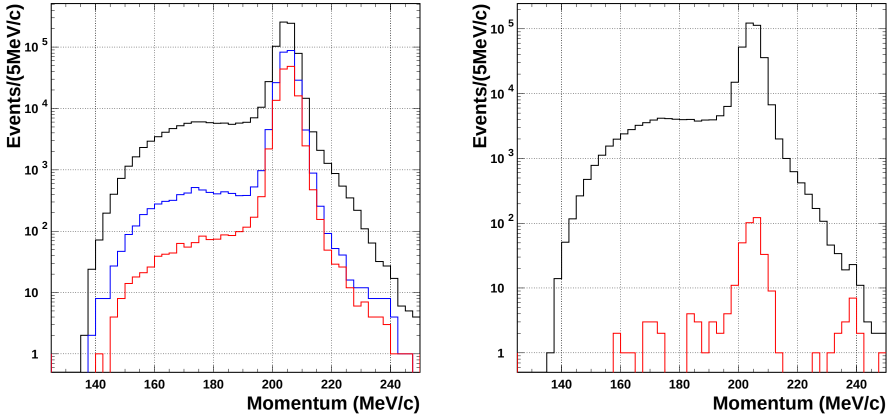


Kink in pattern of target fibers



Excess energy in kaon fibers ("CCDPUL")

Suppression of $K_{\pi 2}$ scatter background



Black: Photon-tagged sample

Blue: After target cuts (except CCDPUL)

Red: After all target cuts

Black: π^+-scatter-tagged sample

Red: After photon veto cuts

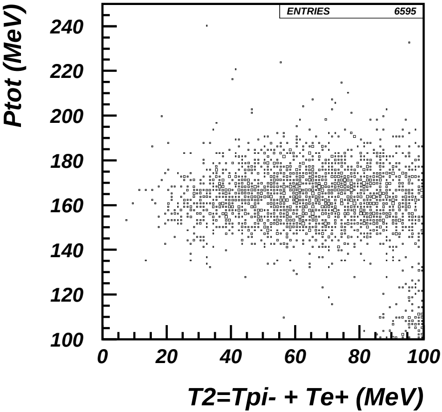
Estimation of $K_{\pi2}$ scattering background

- $K_{\pi2}$ scattering background is suppressed by PV and target cuts.
- To estimate PV rejection, multiple π^+-scattering samples are prepared by inverting different combinations of target cuts.
- The "normalization" sample is estimated by inverting the PV cut, but the sample is contaminated with $K_{\pi2}$ scatters in the range stack (RS) and by $\mathrm{K}^+ \rightarrow \pi^+\pi^0\gamma$.

After disentangling the processes:

Process	Background events
$K_{\pi2}$ TG-scatter	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi2}$ RS-scatter	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi2\gamma}$	$0.076 \pm 0.007 \pm 0.006$

$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4}) background



$K^+ \to \pi^+\pi^- e^+\nu$ can be a background if the π^- and e^+ have very little kinetic energy and evade detection.

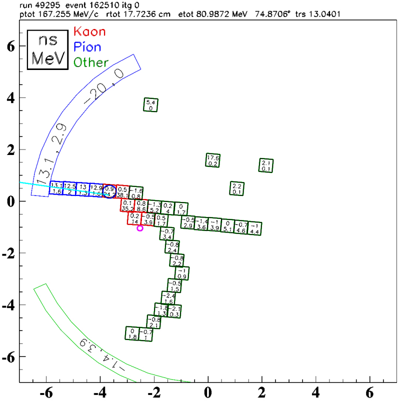
Figure: π^+ momentum (P_π) *vs.* total kinetic energy of π^- and e^+ from simulated $K^+ \to \pi^+\pi^- e^+\nu$ decays.

Signal region is $140 < P_\pi < 199$ MeV/c

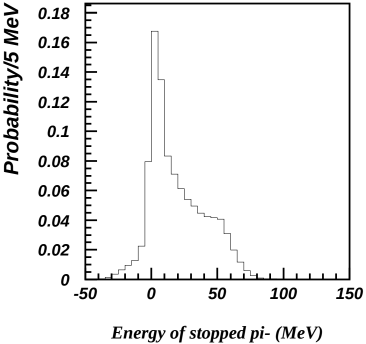
Cannot make a purely data-based background estimate due to inability to isolate K_{e4} from the larger $K_{\pi 2}$-scatter background.

$K^+ \to \pi^+\pi^- e^+\nu$ background

Isolate K_{e4} sample using target pattern recognition, similar to $K_{\pi 2}$ scatter.



Estimate rejection power of target pattern recognition with simulated data supplemented by measured π^- energy deposition spectrum in scintillator.



Total background and sensitivity

Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 0.011	0.016 ± 0.011
Beam	0.001 ± 0.001	0.066 ± 0.045
Total bkgd	$0.93 \pm 0.17^{+0.32}_{-0.24}$	1.22 ± 0.24

	E949 pnn2	E787 pnn2
Total Kaons	1.70×10^{12}	1.73×10^{12}
Total Acceptance	1.37×10^{-3}	0.84×10^{-3}
SES	4.3×10^{-10}	6.9×10^{-10}

The branching ratio that corresponds to one event in the absence of background is the Single-Event Sensitivity (SES).

For the E787+E949 pnn1 analysis, SES $= 0.63 \times 10^{-10}$.

Verification of background estimates

Relax PV and CCDPUL cuts to define 2 distinct regions PV_1 and CCD_1 immediately adjacent to the signal region.

Define a third region PV_2 by further loosening of the PV cut.

Compare the observed ($N_{\rm obs}$) with the expected number ($N_{\rm exp}$) of events in each region.

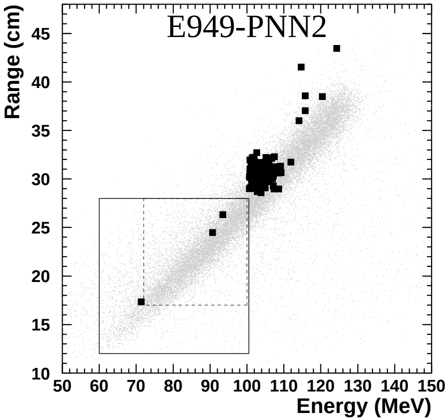
Region	$N_{\rm exp}$	$N_{\rm obs}$
CCD_1	$0.79^{+0.46}_{-0.51}$	0
PV_1	$9.09^{+1.53}_{-1.32}$	3
PV_2	$32.4^{+12.3}_{-8.1}$	34

The probability to observe ≤ 3 events when $9.09^{+1.53}_{-1.32}$ are expected is 2%. The probability of the observation in regions CCD_1 and PV_1 given the expectation is 5%; the expectation is [2%,14%] when the uncertainty in $N_{\rm exp}$ is taken into account.

Division of the signal region

- The background is not uniformly distributed in the signal region.
- Use the remaining rejection power of the photon veto, delayed coincidence, $\pi \to \mu \to e$ and kinematic cuts to divide the signal region into 9 cells with differing levels of signal acceptance (S_i) and background (B_i).
- Calculate $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu})$ using S_i/B_i of any cells containing events using the likelihood ratio method.

Examining the signal region



The nine cells

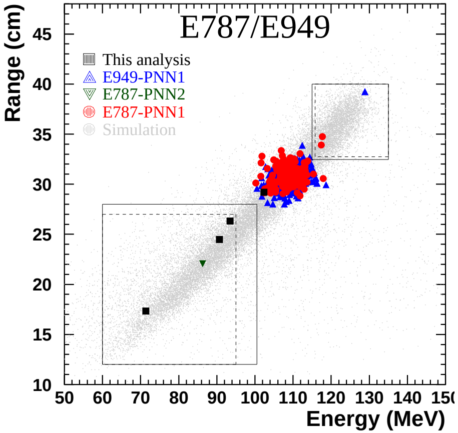
Bkgd	Events	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20

The probability of all 3 events to be due to background only is 0.037.

No momentum cut applied. Solid line represents signal region, dashed line shows tightened kinematic cuts. Gray points are simulated $K^+ \to \pi^+ \nu\bar{\nu}$.

Measured $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ for E949 & E787

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



- The probability of all 7 events to be due to background only is 0.001.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$
- The pnn1 analyses are 4.2 times more sensitive than the pnn2 analyses due to a combination of acceptance and kaon exposure.

E787(dashed) and E949(solid) signal regions shown. All cuts applied.

What happens next?

- In an ill-considered decision of the Executive Branch of the US Government, E949 was cancelled in 2002 after receiving only 20% of the approved beam time.
- Experiment NA62 (formerly NA48/3) at CERN was approved in 2007 and is in preparation.
- NA62 proposes to observe ≈65 $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ with a S/B of ≈10 using a 75 GeV/c beam. The use of kaon decay-in-flight to measure $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ has not been attempted before.
- There is a letter of intent for a stopped kaon decay experiment in Japan.
- "A few % measurement of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ appears feasible at Fermilab Project X or J-PARC." - D.Bryman & L.Littenberg

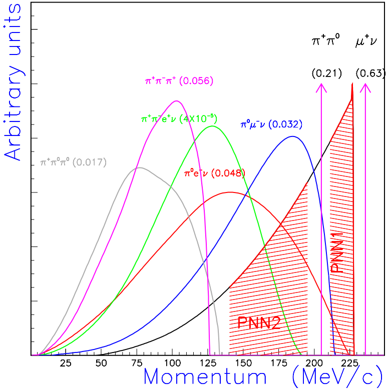
In 25 years of research with BNL E787 and E949, the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays went from a limit on the branching ratio of $< 1.4 \times 10^{-7}$ (90%CL) to a measurement of $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ (arXiv:0808.2459) that is twice as large as, but still consistent with, the Standard Model expectation of $(0.85 \pm 0.07) \times 10^{-10}$.

The techniques, philosophy and results of E949 and E787 have s(h)own the way for experimental searches of rare decays.

BACKUP

Backgrounds in high momentum (pnn1) region

Mechanisms for the main backgrounds in the high momentum region



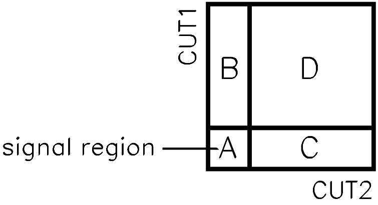
$\mathbf{K^+ \rightarrow \pi^+\pi^0}$ **($K_{\pi2}$)**

1. Mismeasurement of π^+ kinematics
2. Undetected photons from $\pi^0 \rightarrow \gamma\gamma$

$\mathbf{K^+ \rightarrow \mu^+\nu}$ **($K_{\mu2}$)**

1. Mismeasurement of μ^+ kinematics
2. Misidentification of μ^+ as π^+

Estimation of background rates with data



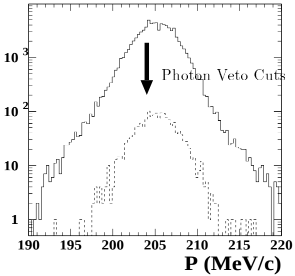
if CUT1, CUT2
uncorrelated,

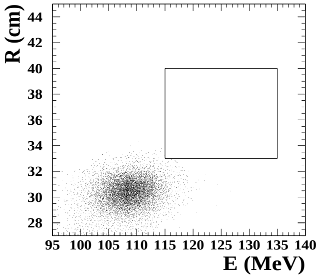
$A/B = C/D$

$A = BC/D$

- Apply cut2 & invert cut1: Select B events
- Invert cut2: Select C+D events
  & apply cut1: Select C events
- Rejection of cut1 is R = (C+D)/C
- Background estimate = B/(R-1)

Example: Estimating $K^+ \to \pi^+\pi^0$ pnn1 background with data

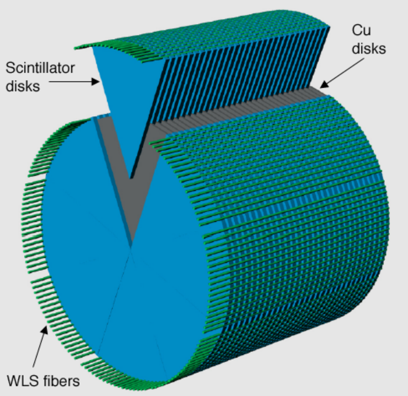




Left: Kinematically selected $K^+ \to \pi^+\pi^0$ with photon veto applied.
Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in P, R, E.

Photon veto in the beam region

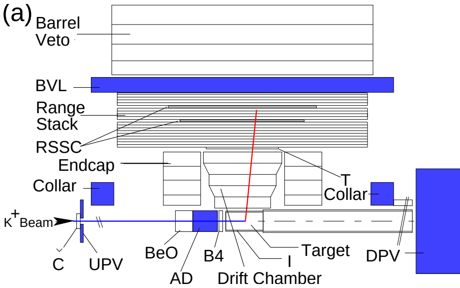


Active Degrader (AD)

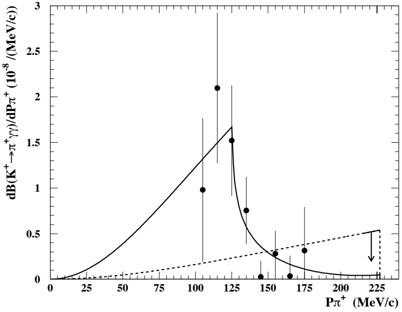
14cm diameter, 17cm long,

12 azimuthal segments

6.1 radiation lengths



$K^+ \to \pi^+\gamma\gamma$ is not a background



Ref: E787, PRL **79**, 4079 (1997).

- Partial branching fraction for $140 < P_\pi < 200\ \mathrm{MeV}/c$ is $\approx 1.1 \times 10^{-7}$.
- Photon veto rejection of $\pi^0 \to \gamma\gamma$ is $> 10^6$.
- Rate of $K^+ \to \pi^+\gamma\gamma$ background is $< 1.1 \times 10^{-13}$ without considerations of π^+ acceptance.