Recent Results from E787/E949

George Redlinger
Brookhaven National Laboratory

Outline

- Brief introduction to E787/E949
- Recent results
  - $K^+ \rightarrow \pi^+ \pi^0 \gamma$ (E787)
  - $K^+ \rightarrow \pi^+ \gamma \gamma$, $K^+ \rightarrow \pi^+ \gamma$ (E949)
  - $\pi^0 \rightarrow \nu\bar{\nu}$ (E949)

E787 Collaboration

UNIVERSITY OF ALBERTA

UBC

BROOKHAVEN NATIONAL LABORATORY

KEK

Princeton

Osaka University

TRIUMF

E949 Collaboration

University of Alberta

UBC

INR,RAS

The University of New Mexico

Brookhaven National Laboratory

Fermilab

Kyoto University

Stony Brook State University of New York

KEK

Osaka University

Fukui University

TRIUMF

IHEP, Protvino

National Defense Academy, Japan

References

$K^+ \rightarrow \pi^+ \pi^0 \gamma$

T. Tsunemi, Univ of Tokyo thesis
KEK K-decay Report 2005-4

$K^+ \rightarrow \pi^+ \gamma \gamma$, $K^+ \rightarrow \pi^+ \gamma$

T. Yoshioka, Univ of Tokyo thesis
KEK K-decay Report 2005-2
hep-ex/0505069, submitted to PLB

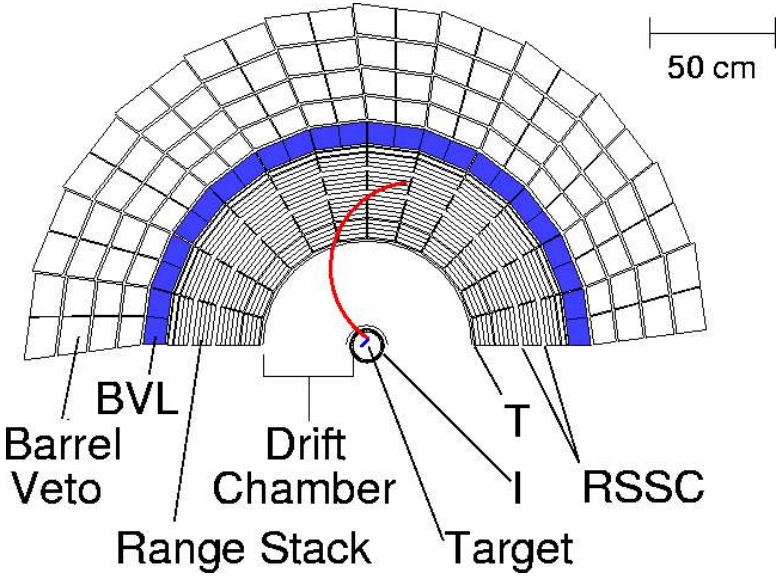
$\pi^0 \rightarrow \nu\bar{\nu}$

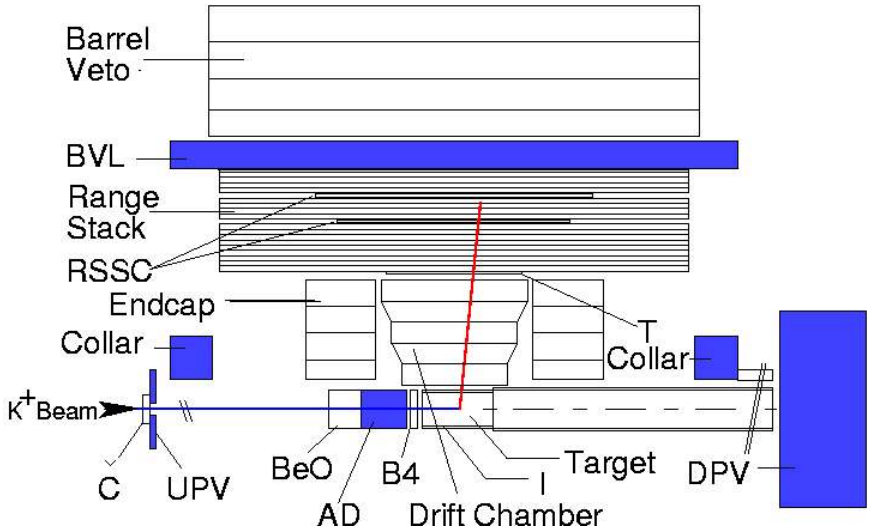
K. Mizouchi, Kyoto Univ thesis (in preparation)
hep-ex/0506028, submitted to PRL

Also see the talks by Tsunemi and Komatsubara plus poster by Mizouchi from the recent KAON 2005 conference

Introduction

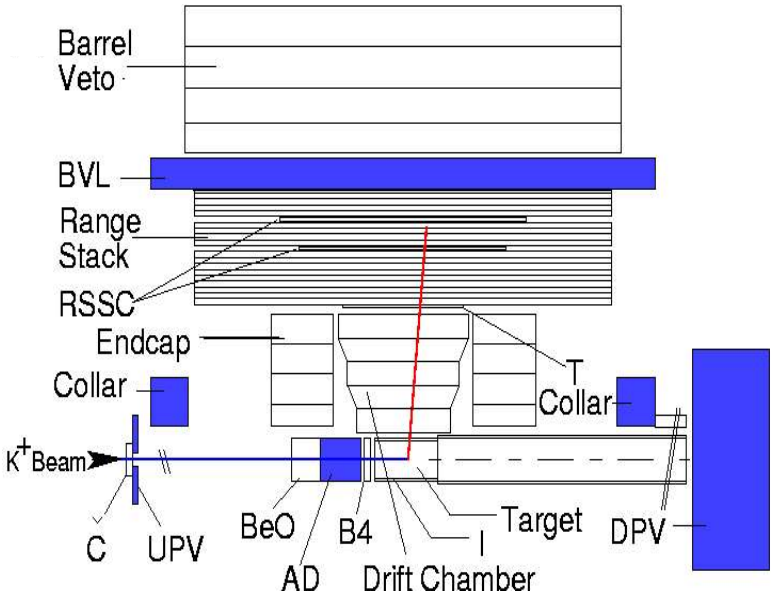
E787/E949 was designed primarily to observe the rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, but other rare modes are accessible, particularly those involving photons

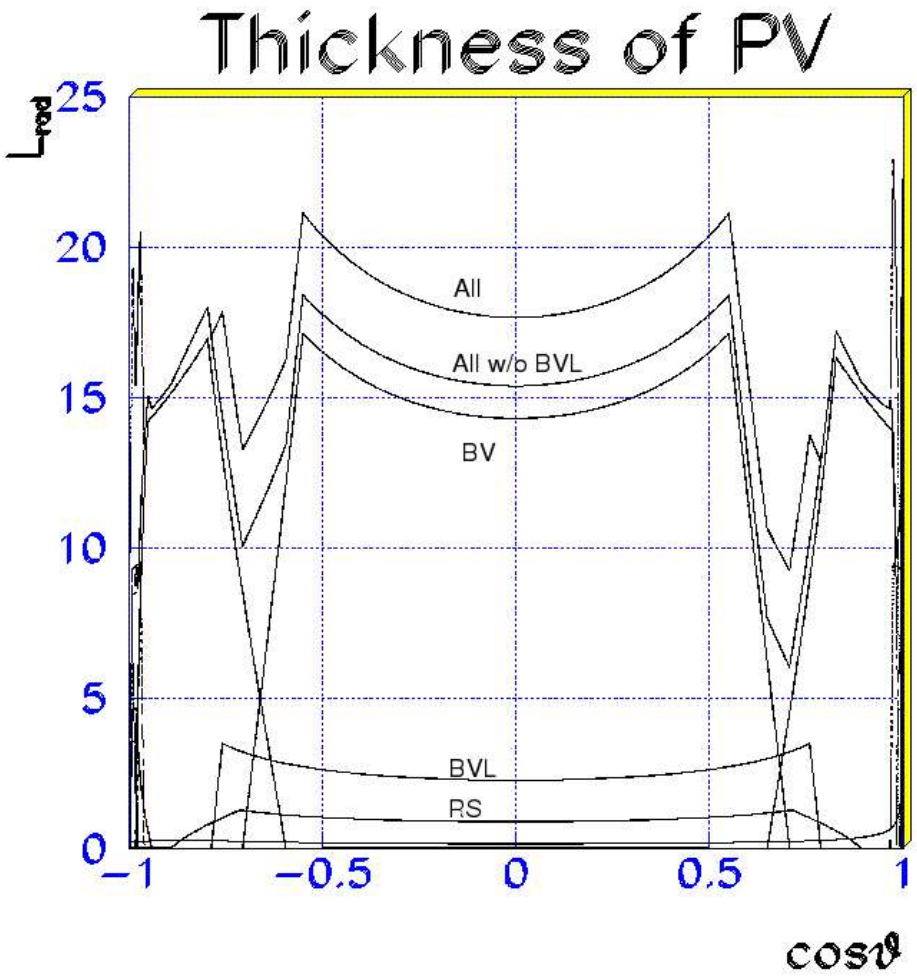




- Incoming beam (~700 MeV/c) tagged by Cerenkov, dE/dx counters
- Stopped kaon beam. Wait ~2ns for K decay (reject beam π). High geometrical acceptance.
- K decay-products momentum analyzed in 10 kG B field.
- Stopped decay pion. Measurement of particle range and energy. Observation of $\pi \rightarrow \mu \rightarrow e$ decay sequence for μ rejection.
- Photon detectors surround everything (E949 PV upgrades shown in blue).

E949 photon detectors

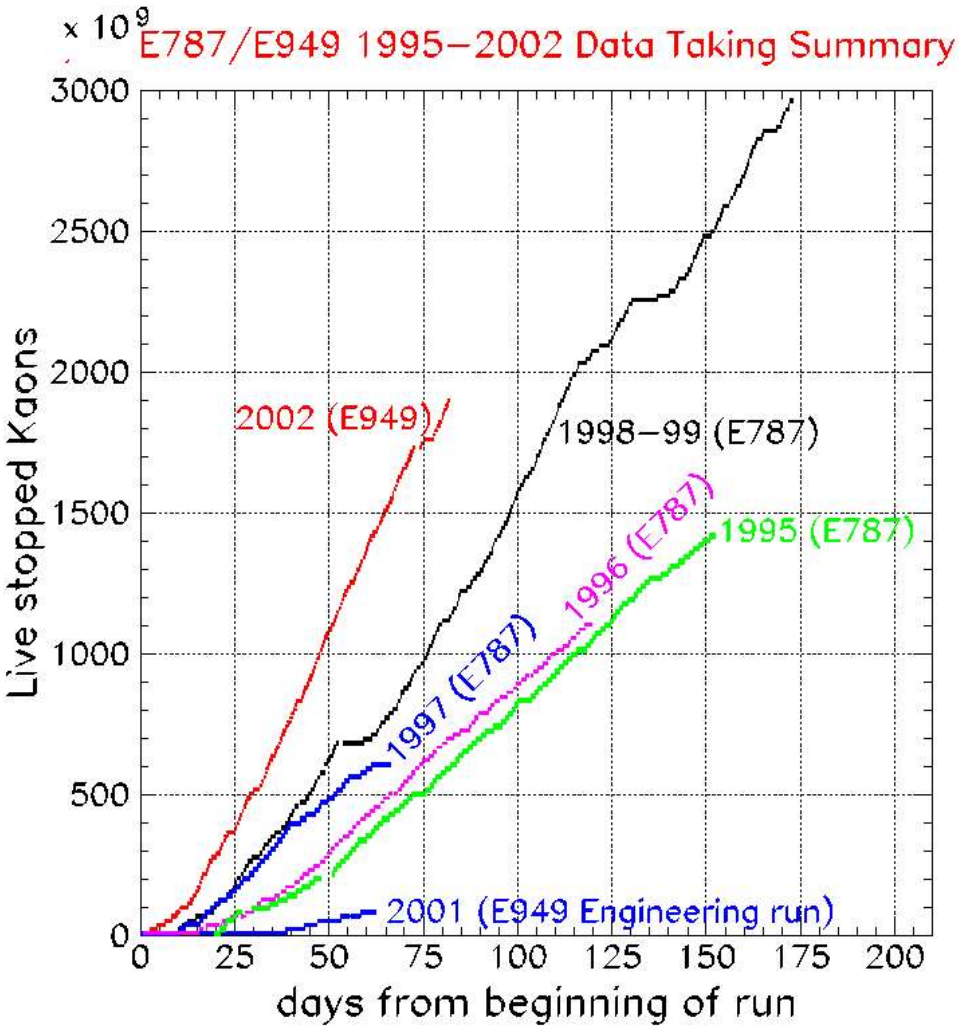




π^0 energy resolution:
$\Delta E/E \sim 0.14$ @ 246 MeV

π^0 rejection:
$\sim O(10^6)$ for $K^+ \rightarrow \pi^+\nu\nu$ analysis

E787/E949 data taking summary



This plot is for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ triggers but gives a rough idea of the kaon exposure.

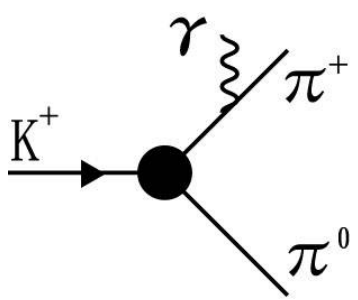
Recall, E949 ran for 12 weeks in 2002 (out of 60 weeks approved) and has not run since then.

2002 run:

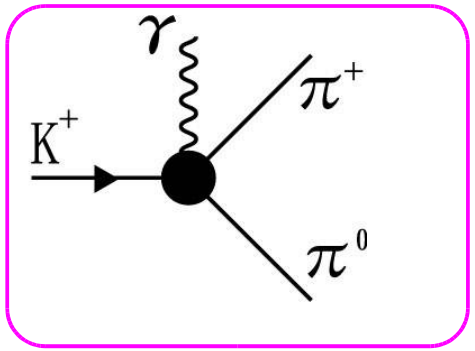
- AGS main power supply problem.
  20% worse duty cycle cf. E787
  Lower p momentum ⇒ ~10% loss in K flux
- K/π separator problems

$K^+ \rightarrow \pi^+\pi^0\gamma$

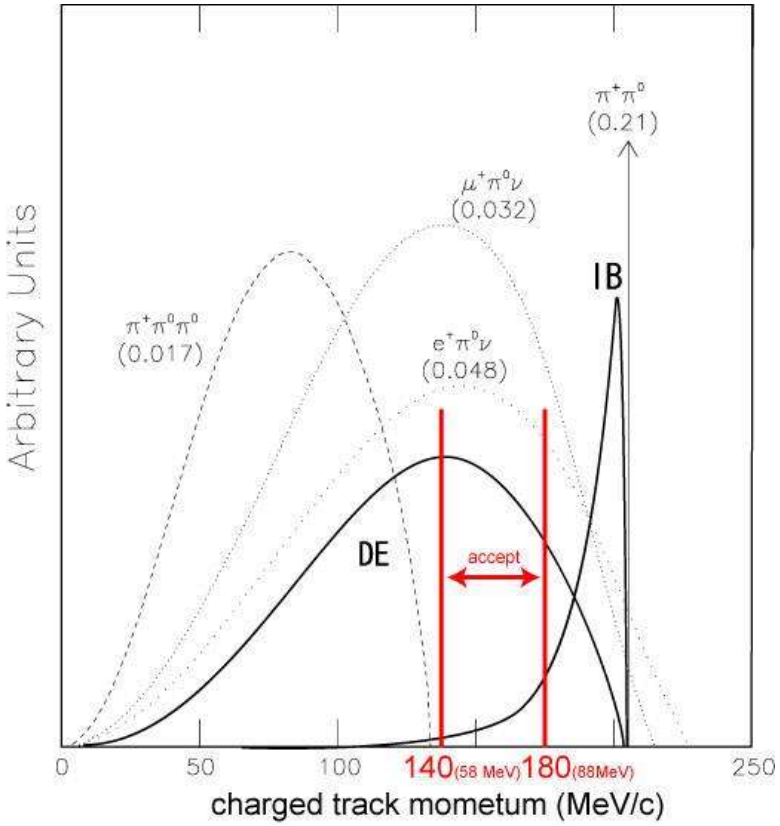
Internal Bremsstrahlung (IB)



Direct Emission (DE)



Focus of this measurement



$BR(K^+ \rightarrow \pi^+ \pi^0 \gamma) = (2.75 \pm 0.15) \times 10^{-4}$ (PDG04)

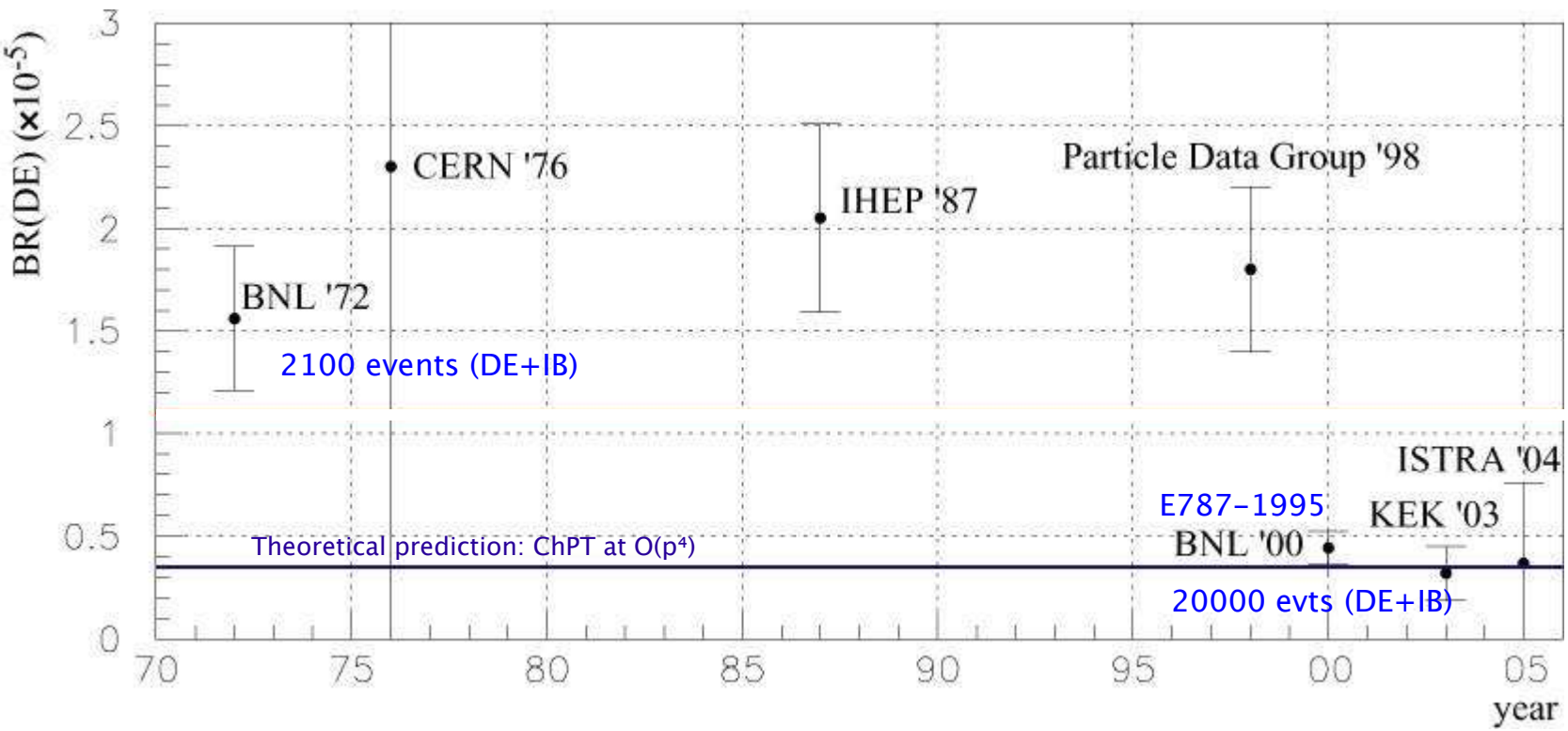
$BR(IB) = 2.61 \times 10^{-4}$ dominates

QED radiative correction to BR(Kπ2)

DE and IB components distinguished by kinematics.

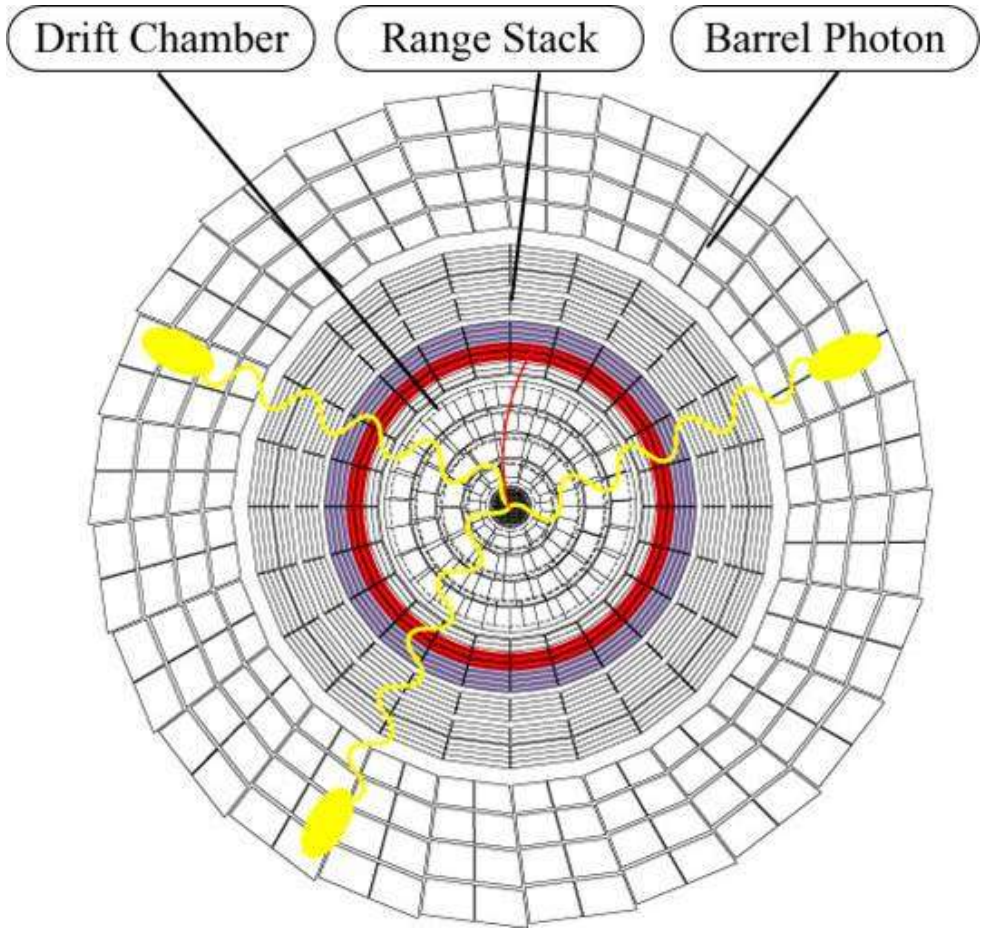
$K^+ \rightarrow \pi^+ \pi^0 \gamma$ history

Measurements of the DE component ($55 < T(\pi^+) < 90$ MeV)



The new measurement is based on the 1998 data set from E787.

$K^+ \rightarrow \pi^+ \pi^0 \gamma$: what was new in 1998



Trigger conditions:

- 3 or more photon clusters (unchanged)
- π^+ stop in RS layers 3–6 (1998)
  - was layers 6–10 in 1995
  - More acceptance for DE component (lower momentum π) in 1998

Number of kaons:

- 3.48×10^{11} (1998)
- 2.83×10^{11} (1995)

Offline analysis

Reconstruction

- Charged track kinematics
- Photon clustering; energy and direction
- Kinematic fit to $K^+ \rightarrow \pi^+ \pi^0 \gamma$

Background estimation

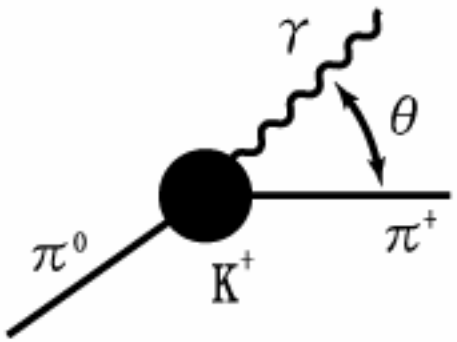
- All backgrounds estimated using the data via "dual cut" technique a la $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ analysis
- 1.3% background in the "DE region"

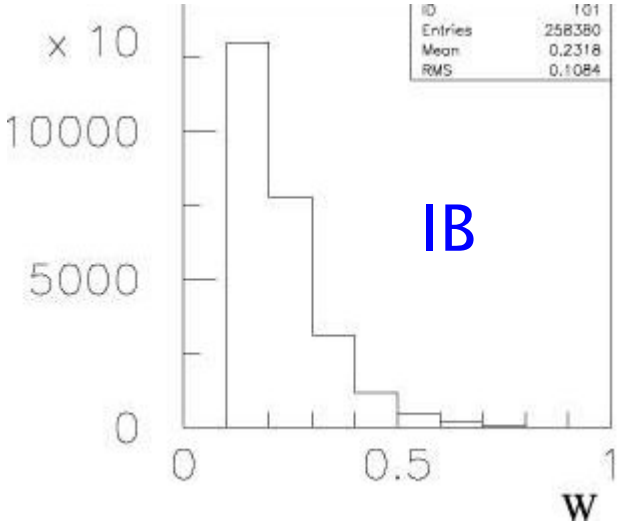
Fit to the W spectrum to extract BR(DE), using BR(IB) to normalize

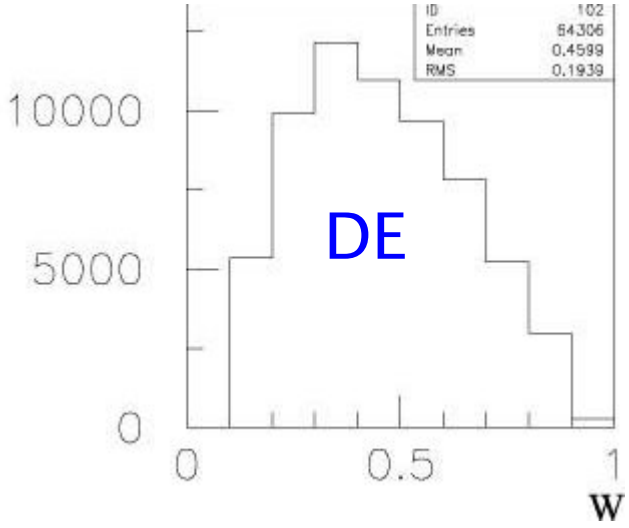
The W variable

In Kaon rest frame:

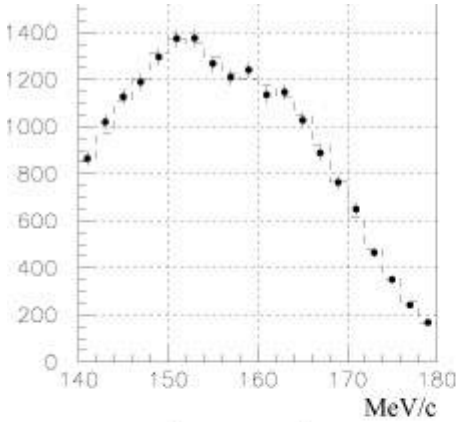
$$W^2 = \frac{E_\gamma^2 (E_{\pi^+} - P_{\pi^+} \cos\theta_{\pi^+\gamma})}{m_K m_{\pi^+}^2}$$



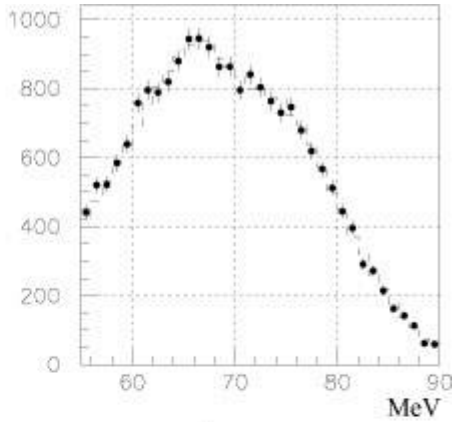




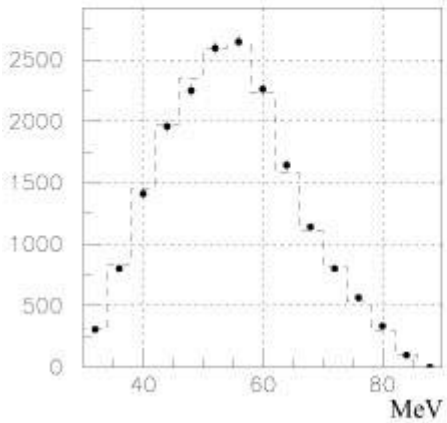
Consistency between data and MC



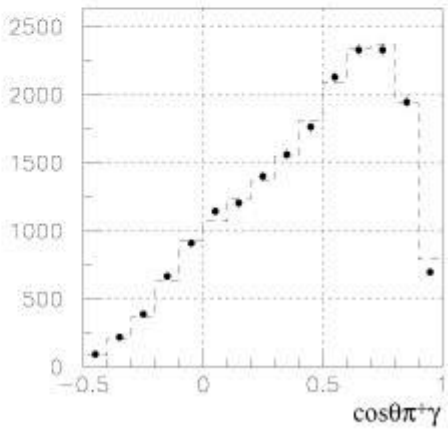
π^+ momentum



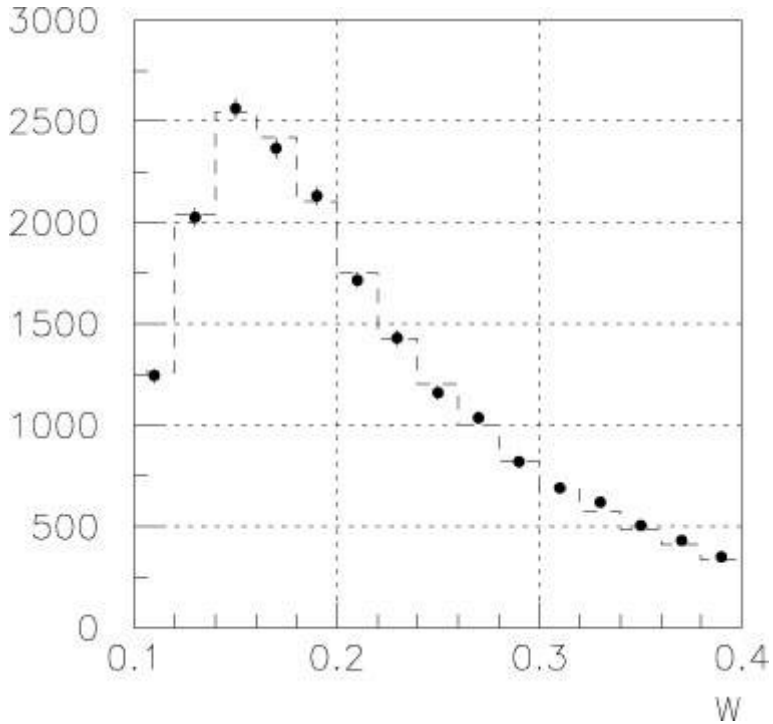
π^+ energy



photon energy

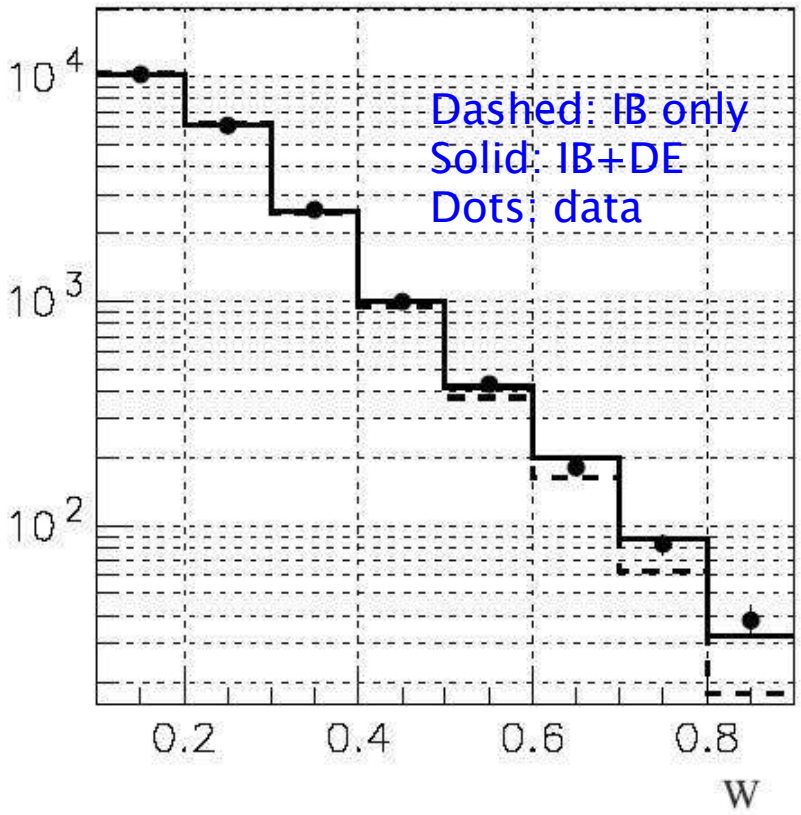


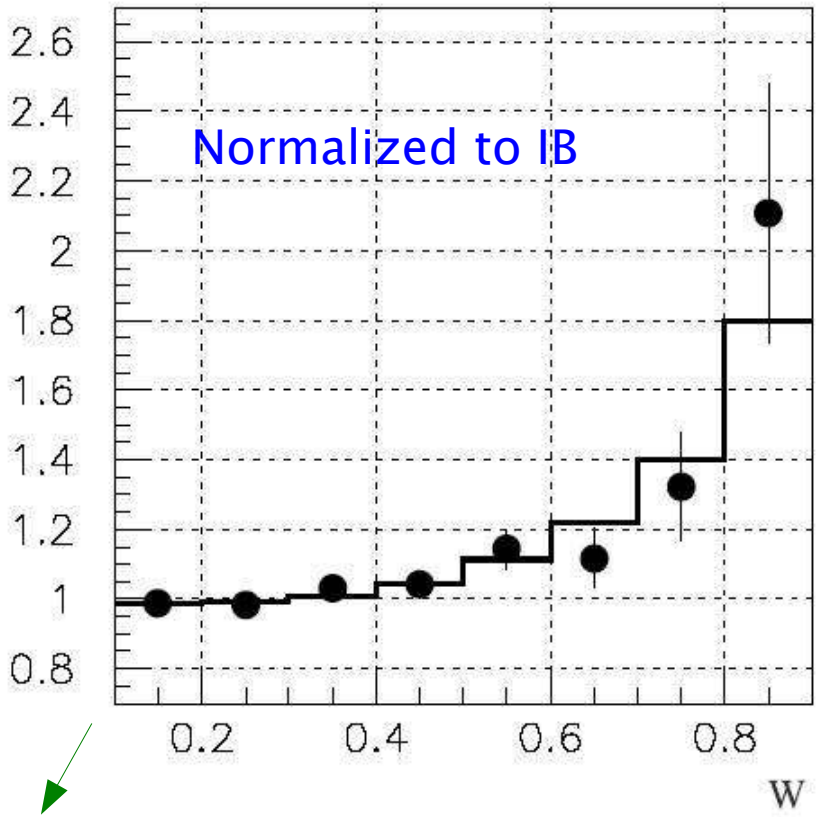
$\cos\theta_{\pi^+\gamma}$



Dots: data
Dashed: Monte Carlo

W spectrum





$BR(K^+ \to \pi^+ \pi^0 \gamma, DE, T(\pi^+)=(55,90)\ MeV) = (3.5 \pm 0.6\ (stat)\ ^{+0.3}_{-0.4}\ (sys)) \times 10^{-6}$

E787 (1998 data) Preliminary.

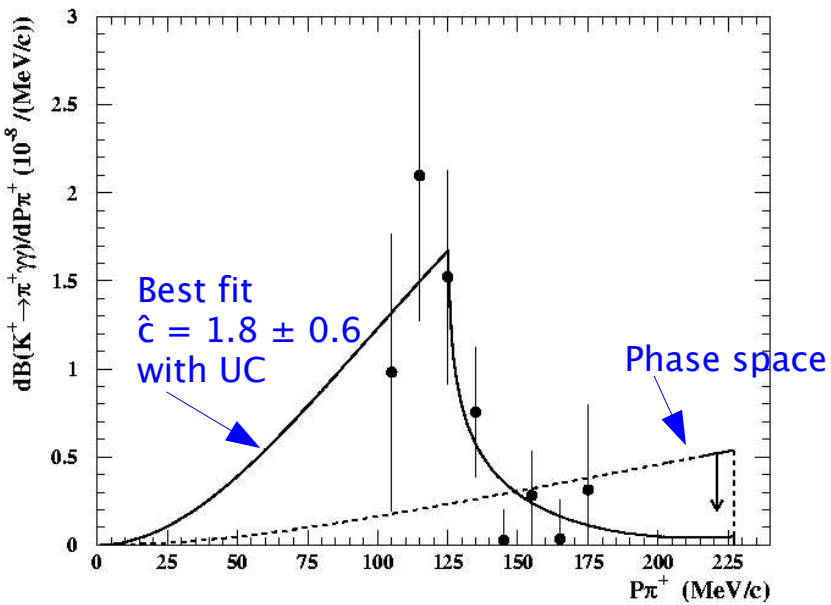
Systematic uncertainty

Ratio of DE to IB

error source	variation	a^{DE} error
pion momentum	+0.3MeV/c	2.8%
	−0.3MeV/c	−2.4%
photon position	−2%	−4.0%
photon position resolution	+0.8cm	−3.3%
visible fraction		negligible
photon interaction		−1.4%
fitting method	the angle	+6.9%
	photon energy	−7.5%
UMC statistics	smaller sample	±2.0%
combined		+8% -10%

$K^+ \to \pi^+ \gamma \gamma$ introduction

First observation was by E787 (Phase I, 1992–1994)



$BR(K^+ \to \pi^+ \gamma \gamma,\ p(\pi) = (110,180)\ MeV/c) =$
$(6.0 \pm 1.5\ (stat) \pm 0.7\ (sys)) \times 10^{-7}$

based on 31 evts with bkg of 5.1 ± 3.3 evts

No events seen for $p(\pi) > 215$ MeV/c

$K^+ \to \pi^+ \gamma \gamma$ introduction

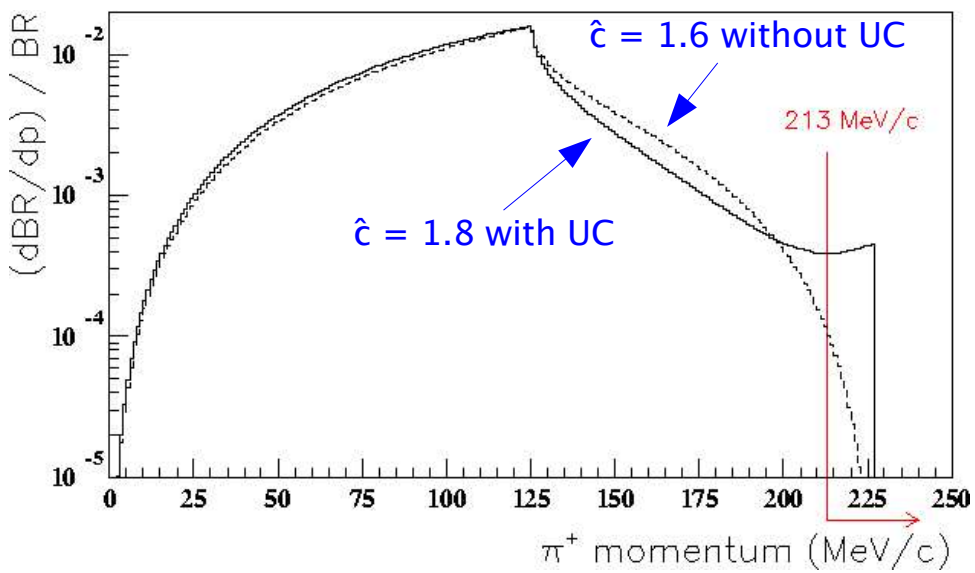
At $O(p^4)$ in ChPT, $BR(K^+ \to \pi^+ \gamma \gamma)$ and spectrum shape depend on a single parameter, $\hat{c}$

So-called "unitarity corrections" (UC) dominate at the next order ($O(p^6)$)

- E787 analysis had a slight preference for UC, but not conclusive

Effect of UC is most dramatic at the π^+ kinematic endpoint (low $M(\gamma\gamma)$)

- E949 focused on this region

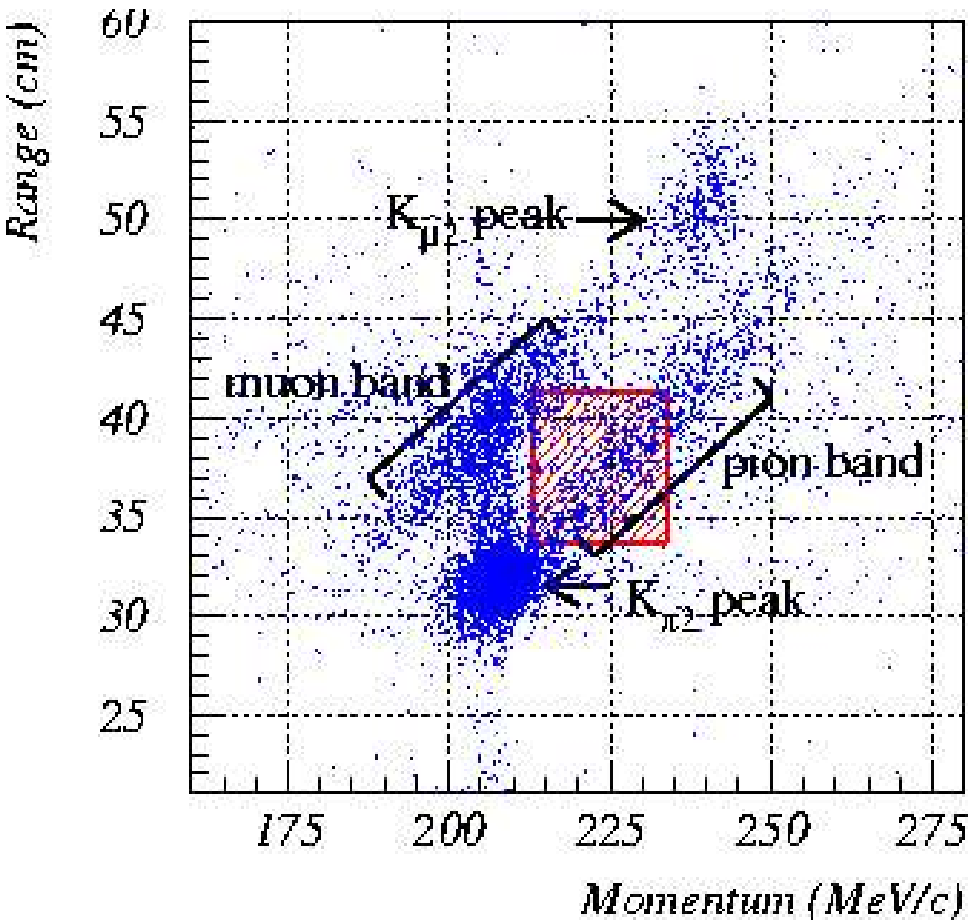


New in E949

- Better trigger, no online prescale!
- Thicker, brighter barrel photon detector

	K exposure	# of triggers
E787	3.1×10^{10}	7.3×10^{5}
E949	1.19×10^{12}	1.1×10^{7}

Offline analysis



Backgrounds:

$K^+ \rightarrow \pi^+\pi^0$ ($K\pi 2$)
- π^+ kinematics mismeasured
- Photon energies/angles mismeasured
- or photon overlaps charged track

$K^+ \rightarrow \mu^+\nu\gamma$, $\pi^0\mu^+\gamma$, or $K\pi 2$ with π DIF
- μ kinematics mismeasured
- $\pi \rightarrow \mu \rightarrow e$ decay sequence fooled

$K\pi 2$ with K DIF
- Fakes K decay at rest
- Suppressed with redundant timing cuts

Two beam particles
- Suppressed with good segmentation and timing in the K tracking system

Background and acceptance

Signal box blinded.

Background levels are estimated from the data using the "dual cut" technique (a la $K^+ \rightarrow \pi^+\nu\nu$ analysis)

1/3 of the data is used for setting the cuts

Cuts are fixed and then applied to the remaining data to estimate the background in an unbiased way.

Background estimates are checked by comparing prediction to observation near the signal region.

Most acceptance factors measured from the data. Monte Carlo is used for trigger acceptance, fiducial cuts, phase space, γ reconstruction and PV cuts that depend on kinematics

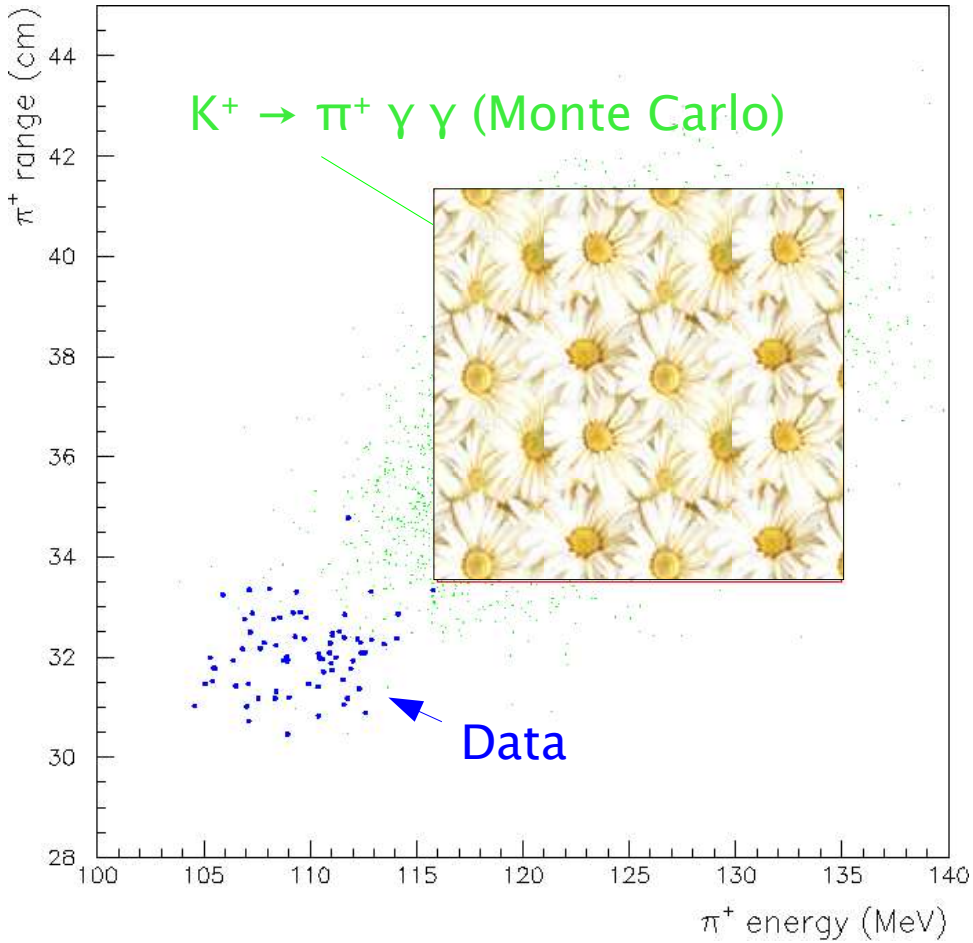
Summary of backgrounds

Background	Number of events
Kπ2	0.017 ± 0.006
Overlapping photon	0.065 ± 0.065
Muon	0.090 ± 0.020
K decay in flight	0.025 ± 0.014
Two beam	< 0.006 (90% CL)
Total	0.197 ± 0.070

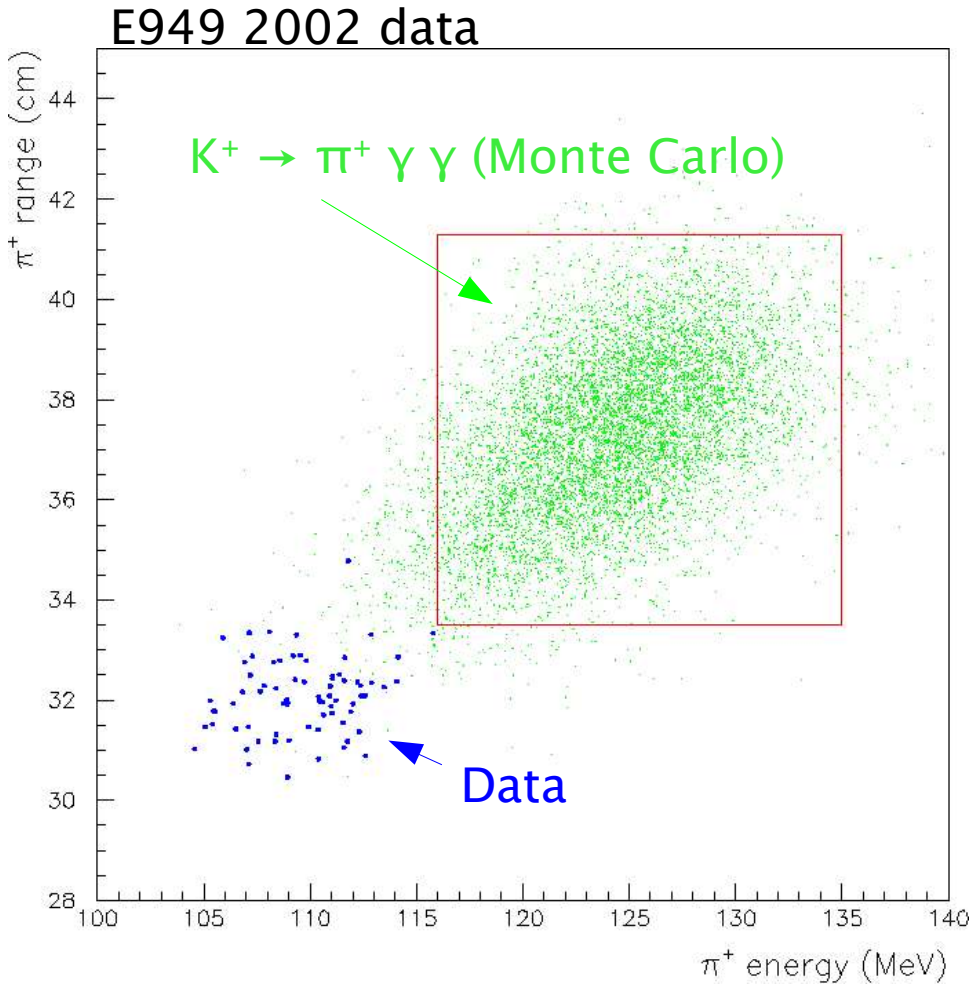
Acceptance and sensitivity

	including unitarity corrections $\hat{c} = 1.8$	without the corrections $\hat{c} = 1.6$
Total acceptance ($P_{\pi^+} > 213$ MeV/c)	$(2.99 \pm 0.07) \times 10^{-4}$	$(1.10 \pm 0.04) \times 10^{-4}$
N_K	1.19×10^{12}	
K^+ stopping efficiency ($K_{\pi 2}$ decays in the trigger)	0.754 ± 0.024	
Single Event Sensitivity	$(3.72 \pm 0.14) \times 10^{-9}$	$(10.1 \pm 0.5) \times 10^{-9}$
predicted branching ratio ($P_{\pi^+} > 213$ MeV/c)	6.10×10^{-9}	0.49×10^{-9}
expectation	1.6 events	0.05 events

$K^+ \rightarrow \pi^+ \gamma \gamma$ result



$K^+ \rightarrow \pi^+ \gamma \gamma$ result



No events seen in the signal box

$BR(K^+ \rightarrow \pi^+ \gamma \gamma) < 8.3 \times 10^{-9}$ (90% CL)
$p(\pi) > 213$ MeV/c

assuming spectrum from ChPT
with unitarity corrections ($\hat{c} = 1.8$)

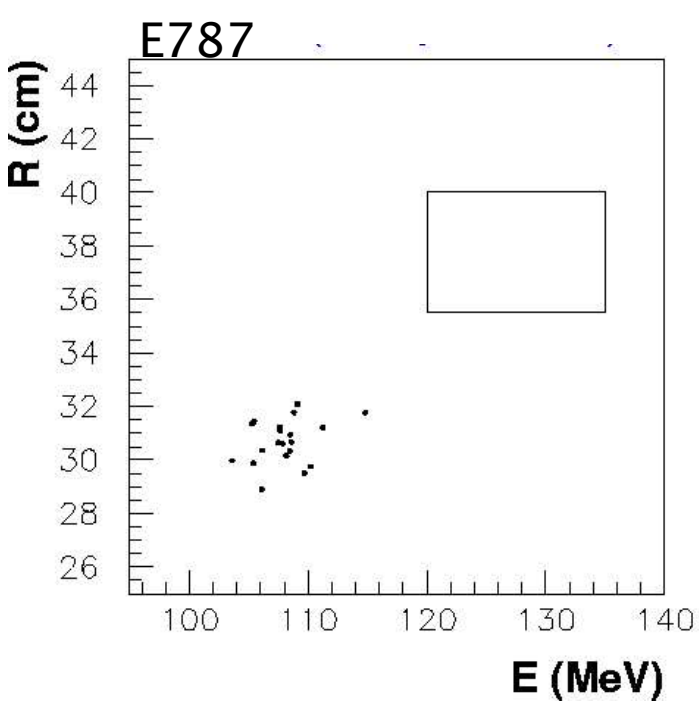
Factor of 8 sensitivity improvement over E787.

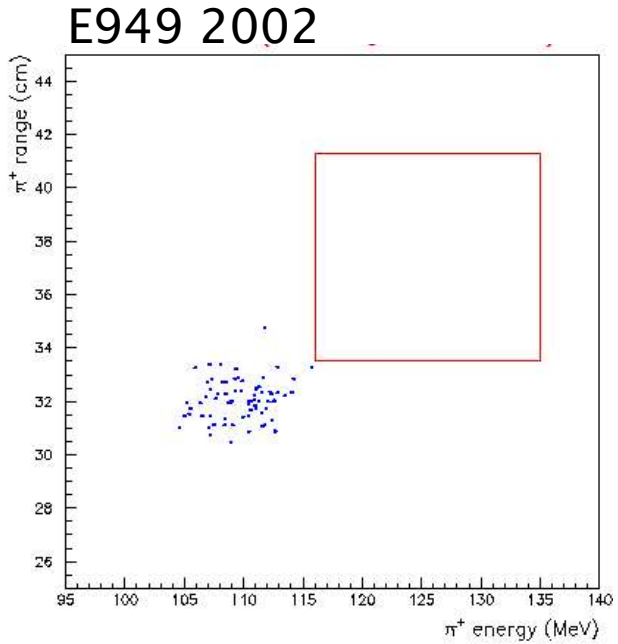
But cannot confirm nor rule out unitarity corrections, unfortunately.

$K^+ \rightarrow \pi^+ \gamma$

The same dataset as for $K^+ \rightarrow \pi^+ \gamma \gamma$ was used to search for $K^+ \rightarrow \pi^+ \gamma$

$K^+ \rightarrow \pi^+ \gamma$ is forbidden by angular-momentum conservation and gauge invariance, but is allowed in "exotic" models such as non-commutative QED





$BR(K^+ \rightarrow \pi^+ \gamma) < 2.3 \times 10^{-9}$ (90% CL)

Factor ~160 improvement over E787

$\pi^0 \rightarrow \nu\bar{\nu}$

Forbidden by angular momentum conservation if neutrinos are purely left-handed, but can proceed if neutrinos have mass.

$BR(\pi^0 \rightarrow \nu\bar{\nu}) < 1.1 \times 10^{-9}$ for $m(\nu_\tau) < 18.2$ MeV/c^2

Best previous experimental limit comes from E787:
$BR(\pi^0 \rightarrow \nu\bar{\nu}) < 8.3 \times 10^{-7}$ (90% CL)

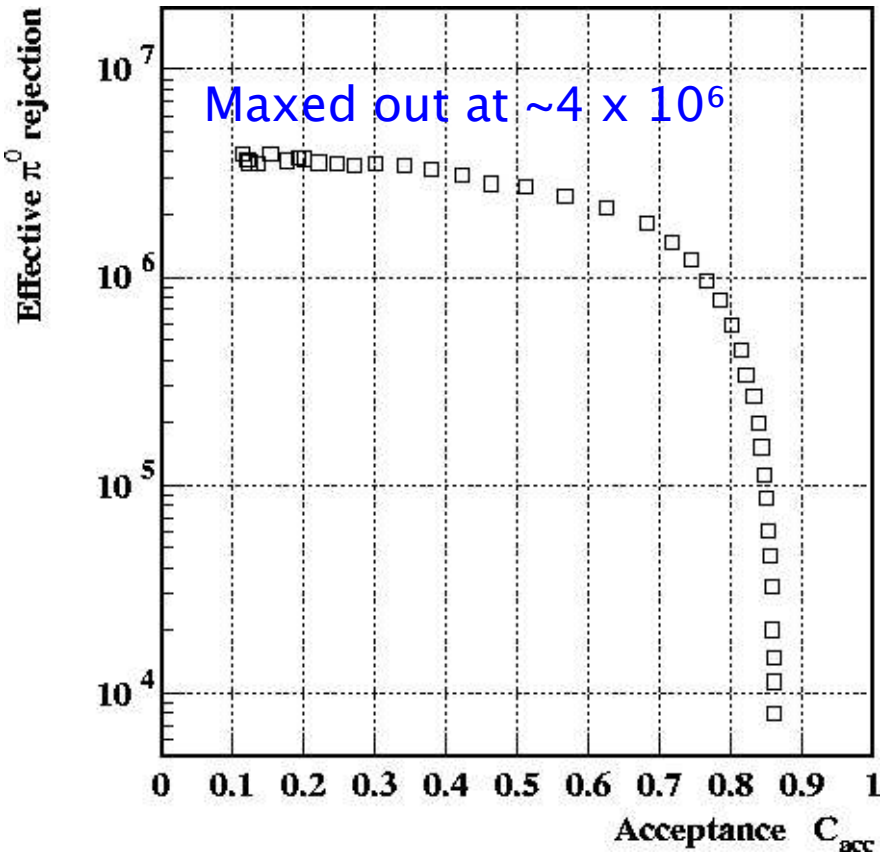
Method: copious supply of π^0 from $K^+ \rightarrow \pi^+ \pi^0$ cleanly tagged by monochromatic π^+
Look for $K\pi2$ events with no activity other than K^+ and π^+

Trigger sample is same as $K^+ \rightarrow \pi^+\nu\nu$. Select $K\pi2$ events. Apply the tightest photon veto.

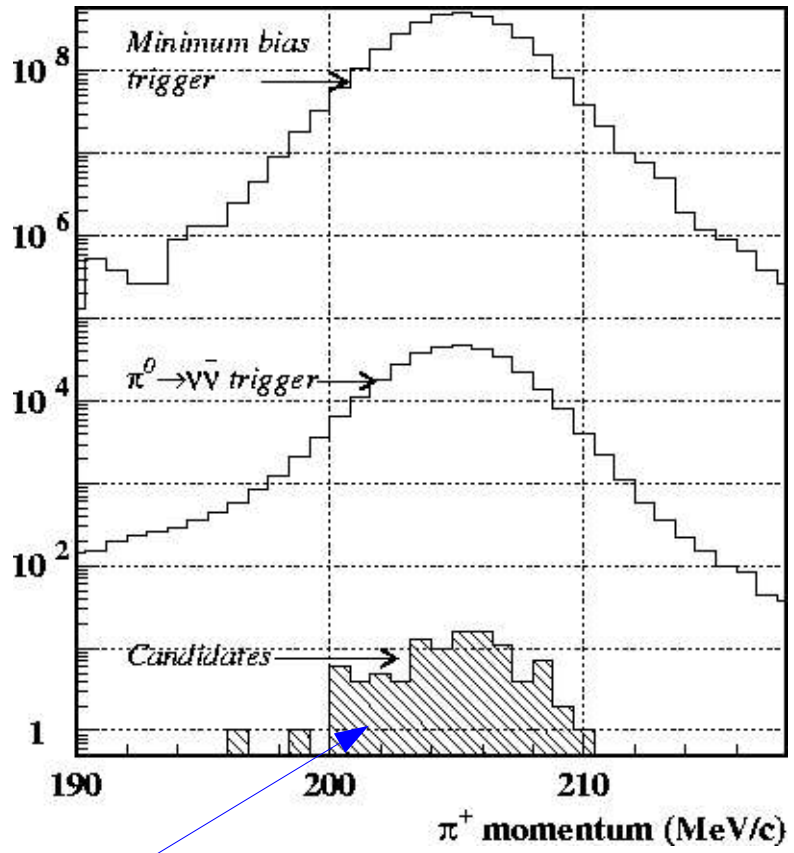
Tune the photon veto on 1/3 of the data. Use 2/3 of the data for the $\pi^0 \rightarrow \nu\bar{\nu}$ search

π^0 *rejection*

Rej x Acc



$N(\pi^0) = 3.02 \times 10^9$



99 events survived all the cuts

$\pi^0 \rightarrow \nu\bar{\nu}$ result

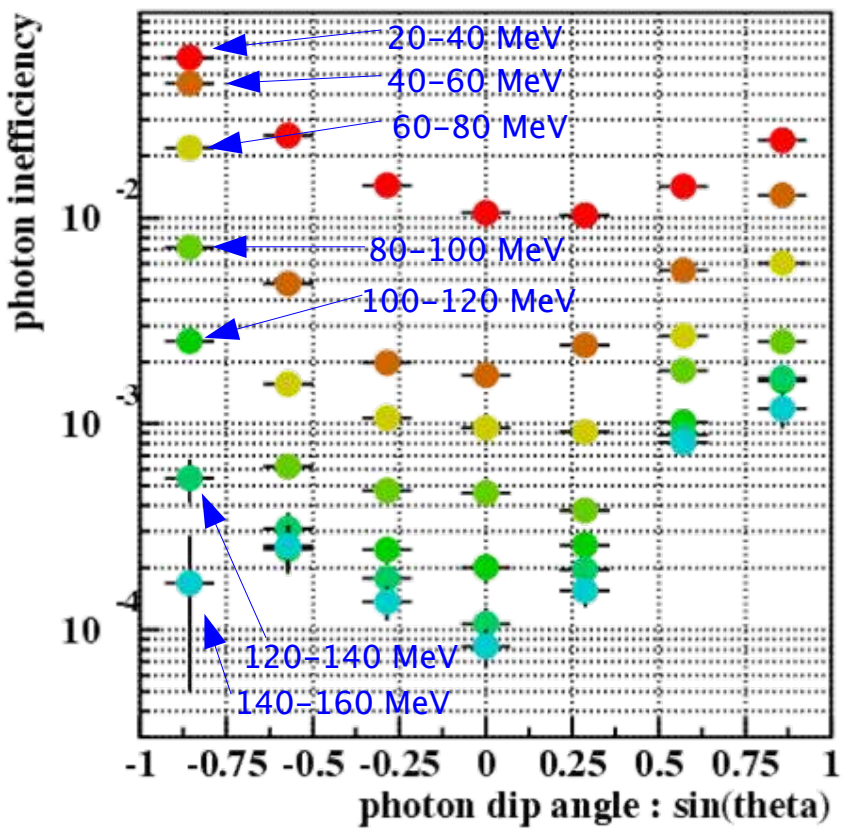
The 99 surviving events are presumed to be $\pi^0 \rightarrow \gamma\gamma$ where the photons are not detected, either due to sampling fluctuations (only for E~20 MeV) or due to photonuclear interactions with undetected products.

We have not fully understood the photon detection inefficiency in E949, so we do not attempt to subtract this background.

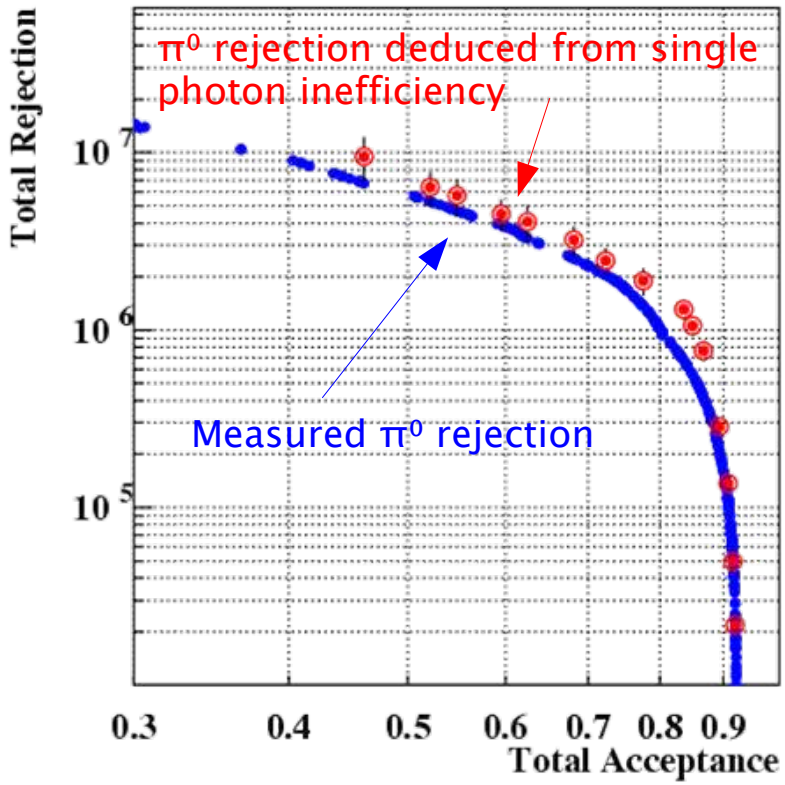
Treating the 99 events as candidates, we obtain $BR(\pi^0 \rightarrow \nu\bar{\nu}) < 2.7 \times 10^{-7}$ (90% CL)

Factor of 3 improvement over E787.

Single photon detection inefficiency



Important byproduct is the measurement of the single photon detection ineff. Critical parameter for KOPIO and other future K → πνν experiments.



Conclusion

E787/E949, although optimized for $K^+ \to \pi^+\nu\bar{\nu}$, is sensitive to a number of other rare decay modes, particularly those involving photons

From E787 (1998 data)

- $BR(K^+ \to \pi^+ \pi^0 \gamma$, DE, $T(\pi^+)=(55,90)$ MeV) $= (3.5 \pm 0.6\ (stat)\ ^{+0.3}_{-0.4}\ (sys)) \times 10^{-6}$
- Still preliminary

From E949 (2002 data)

- $BR(K^+ \to \pi^+ \gamma \gamma) < 8.3 \times 10^{-9}$ (90% CL), $p(\pi) > 213$ MeV/c
- $BR(K^+ \to \pi^+ \gamma) < 2.3 \times 10^{-9}$ (90% CL)
- $BR(\pi^0 \to \nu\bar{\nu}) < 2.7 \times 10^{-7}$ (90% CL)
- These are the most stringent limits available for these decay modes

Still to come:

- $BR(K^+ \to \pi^0\mu^+\nu\gamma)$
- $BR(K^+ \to \pi^+\nu\bar{\nu})$ in "region 2", $p(\pi) < 195$ MeV/c