Recent Results from BNL-E949 on the Rare Decays $K^+ \to \pi^+\gamma\gamma$, $\pi^+\gamma$

Takeshi K. Komatsubara (KEK-IPNS)

representing the E949 collaboration

- `arXiv:hep-ex/0505069`
- T.Yoshioka, Ph.D thesis (U.Tokyo, 2005)

another Golden Needle

in a Micro-Cosmic Haystack

Kaon 2005 International Workshop, June 15, 2005

Outline [in the 20 slides, 25 minutes]

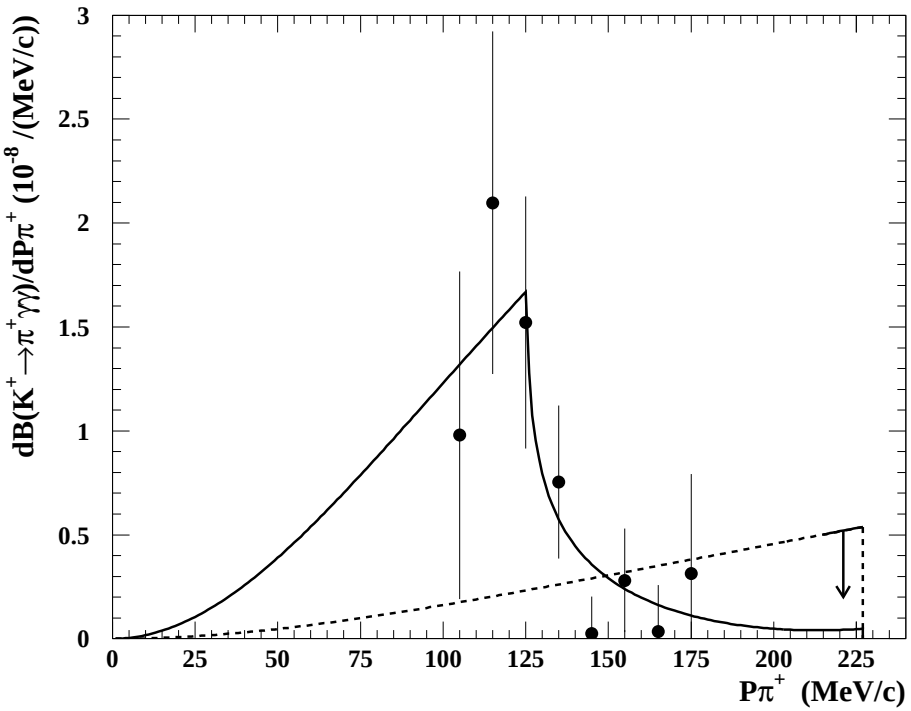
- $\mathbf{K^+ \to \pi^+\gamma\gamma}$ in the region $P_{\pi^+} > 213$ MeV/c and Chiral Perturbation Theory
- E949 "gamma" dataset and analysis
- results
- $\mathbf{K^+ \to \pi^+\gamma}$ far beyond the SM

byproducts of E949 in 2002 dataset

- Canada: TRIUMF, Alberta, British Columbia
- Japan: KEK, RCNP, Fukui, Kyoto, Osaka, NDA
- Russia: IHEP, INR
- US: BNL, FNAL, Stony Brook, New Mexico

E787: Observation of $K^+ \to \pi^+\gamma\gamma$

E787 in 1991 dataset, before the major upgrades (1992-94)

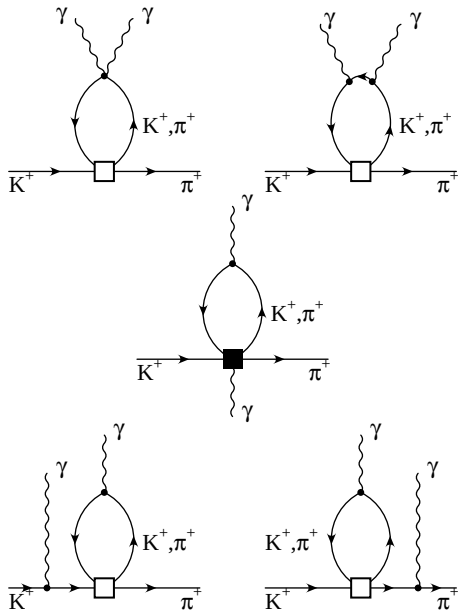


PRL 79 (1997) 4079

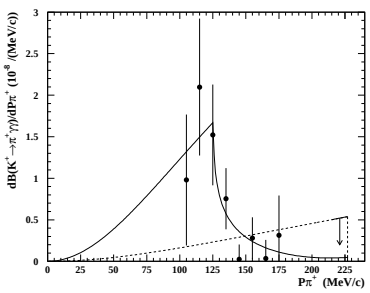
- $100 < P_{\pi^+} < 180$ MeV/c (large $M_{\gamma\gamma}$):
  31 events with 5.1 ± 3.3 bgd
  B(100< P_{π^+} <180MeV/c) $= (6.0 \pm 1.5_{stat} \pm 0.7_{syst}) \times 10^{-7}$
- $P_{\pi^+} > 215$ MeV/c (small $M_{\gamma\gamma}$): no events

$K^+ \to \pi^+\gamma\gamma$ in Chiral Perturbation Theory (ChPT)

leading contribution at $O(p^4)$

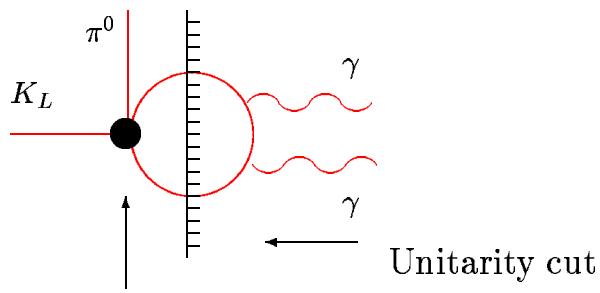


undetermined coupling-constant $\hat{c}$



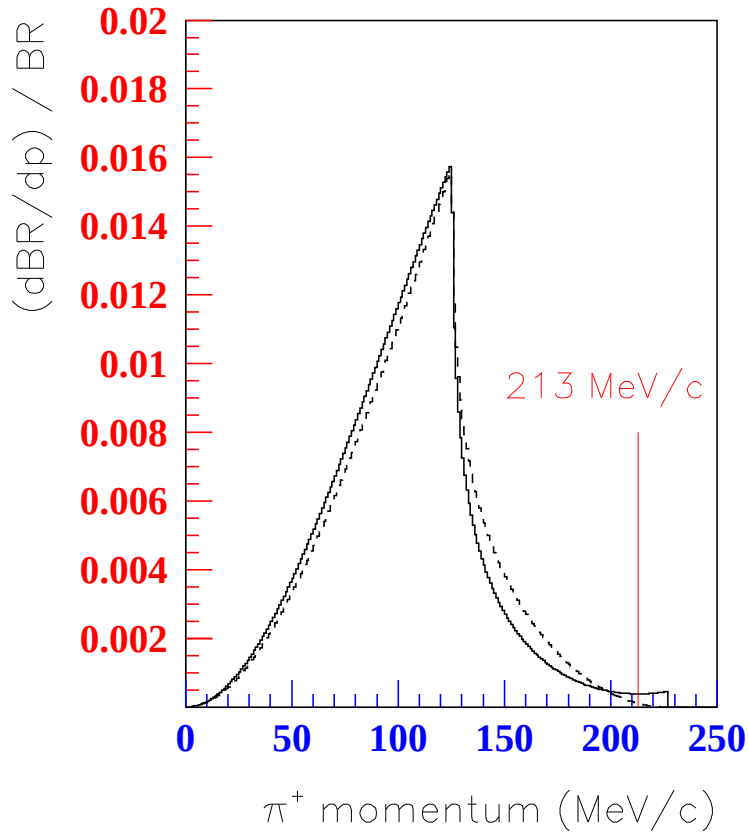
NLO contribution at $O(p^6)$

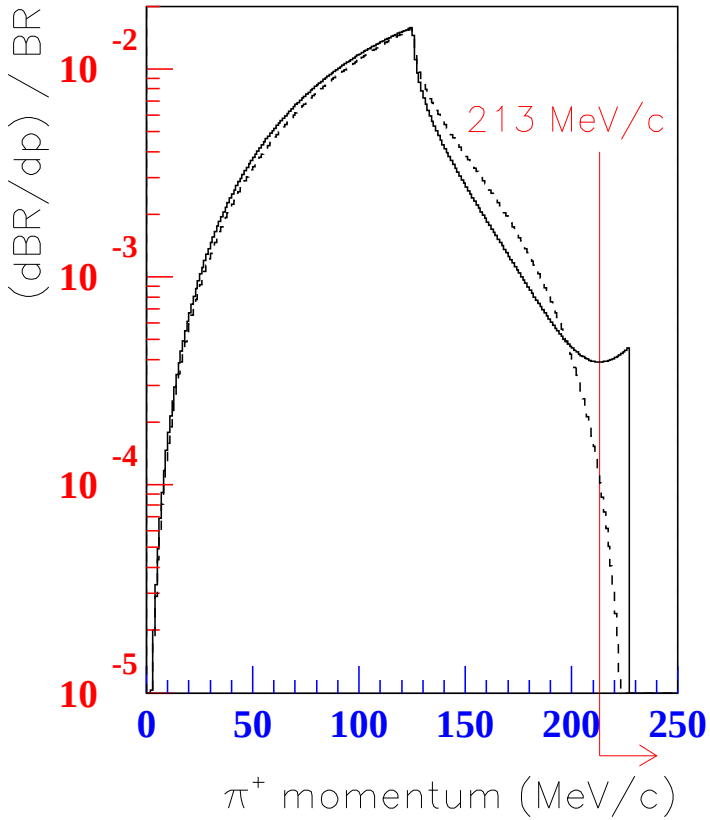
- "unitarity" corrections with $\hat{c}$



$$A(K \to 3\pi) = a + b\,Y + c\,Y^2 + d\,X^2$$

- Vector-Meson exchange
  negligible in $K^+ \to \pi^+\gamma\gamma$
  important in $K_L^0 \to \pi^0\gamma\gamma$ (a_v)
- other new dynamics ??





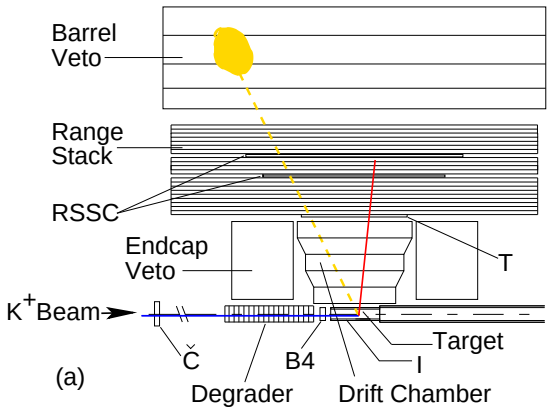
the measured π^+ spectrum in E787:

- including unitarity corrections:
  $\hat{c} = 1.8 \pm 0.6$ (solid)
- without the corrections:
  $\hat{c} = 1.6 \pm 0.6$ (dashed)

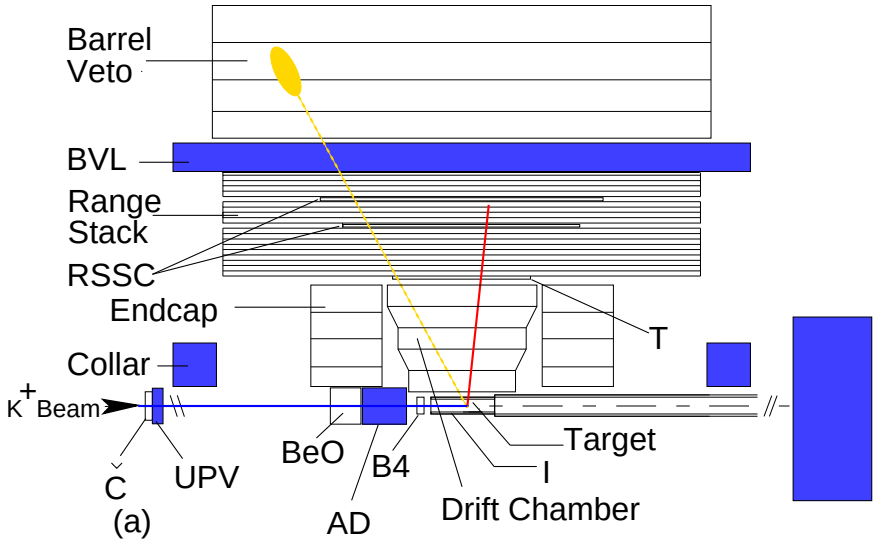
the partial BR P_{π^+} >213MeV/c:

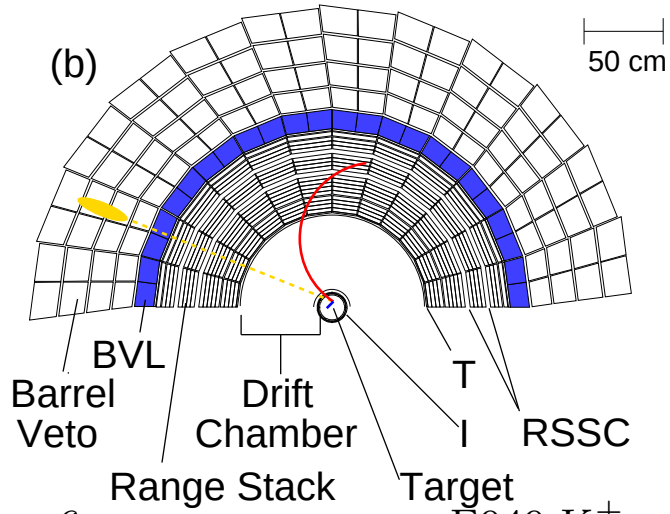
- including unitarity corrections:
  $6.10^{+0.16}_{-0.12} \times 10^{-9}$
- without the corrections:
  $0.49^{+0.23}_{-0.18} \times 10^{-9}$

E787 and E949: K^+ decays at rest

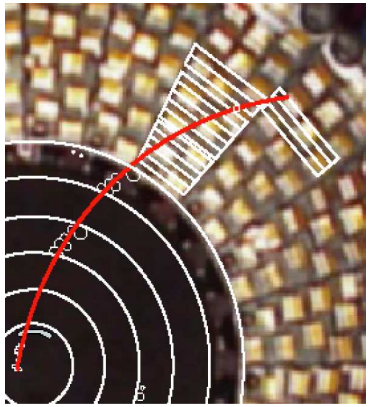


- E787: major upgrades of the beam line and detector after the $\mathrm{K}^+ \to \pi^+\gamma\gamma$ study (and we observed the $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ decay !)
- E949:
  - new Calorimeters: Barrel Veto Liner (2.3 X_0), ancillary systems along the beam direction
  - Level0 trigger board and digital Meantimers



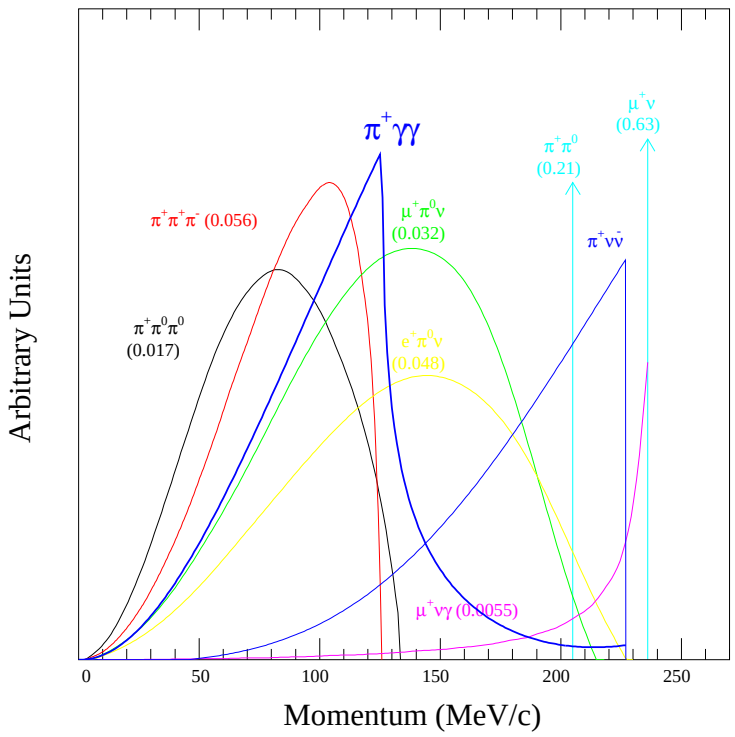


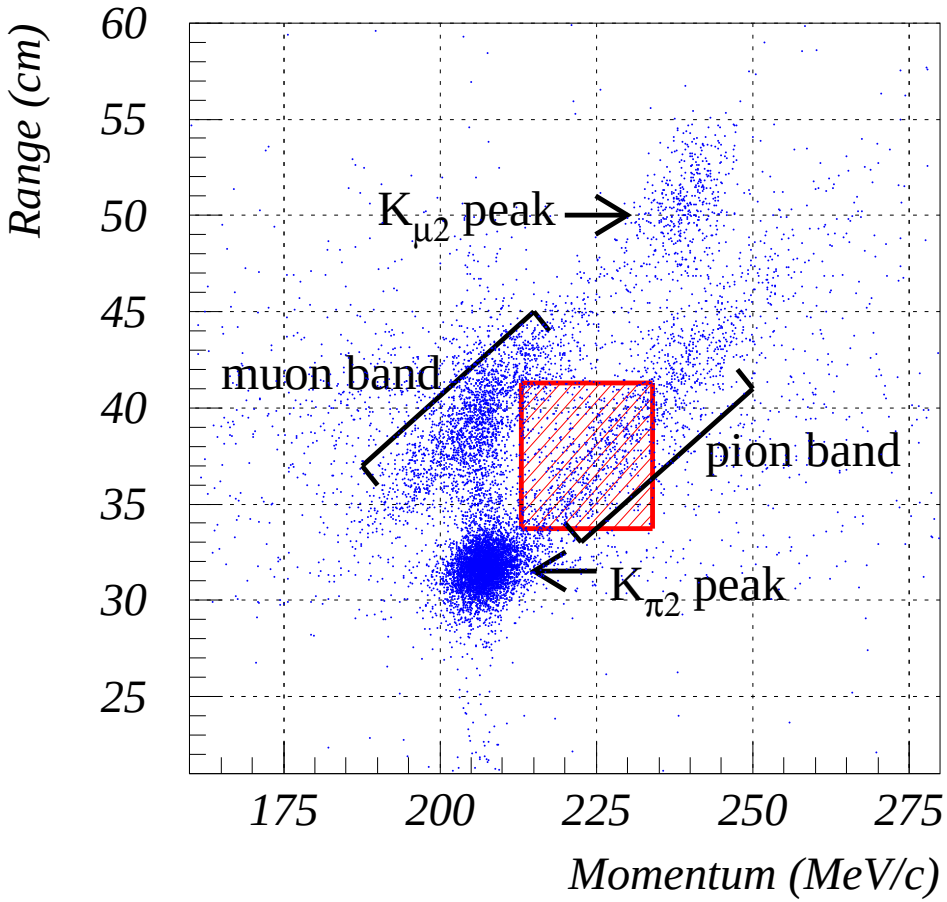
Trigger requirements (π^+ "above the $K_{\pi 2}$ peak")



	E787-$\pi^+\gamma\gamma$	E949-$\pi^+\gamma\gamma$	E949-$\pi^+\nu\bar{\nu}$
Beam	K^+ at rest in the target to decay		
charged track	I-counters and T-counters		
RS stopping layer (π^+ range)	15,16,17,18	16,17	from 11 to 18
$K_{\mu 2(\gamma)}$ suppression with kinematics	range, energy	–	range
π^+ identification	$\pi^+ \to \mu^+$ in the stopping counter		
γ	shower in the barrel part		no shower
	no extra shower in RS, Endcap		
Level-3 γ clustering	○	–	–
prescale factor	2	–	–
K^+ exposure	3.1×10^{10}	1.2×10^{12}	1.8×10^{12}
# of triggered events	7.3×10^5	1.1×10^7	9.0×10^7

Charged Tracks in the trigger, and background sources



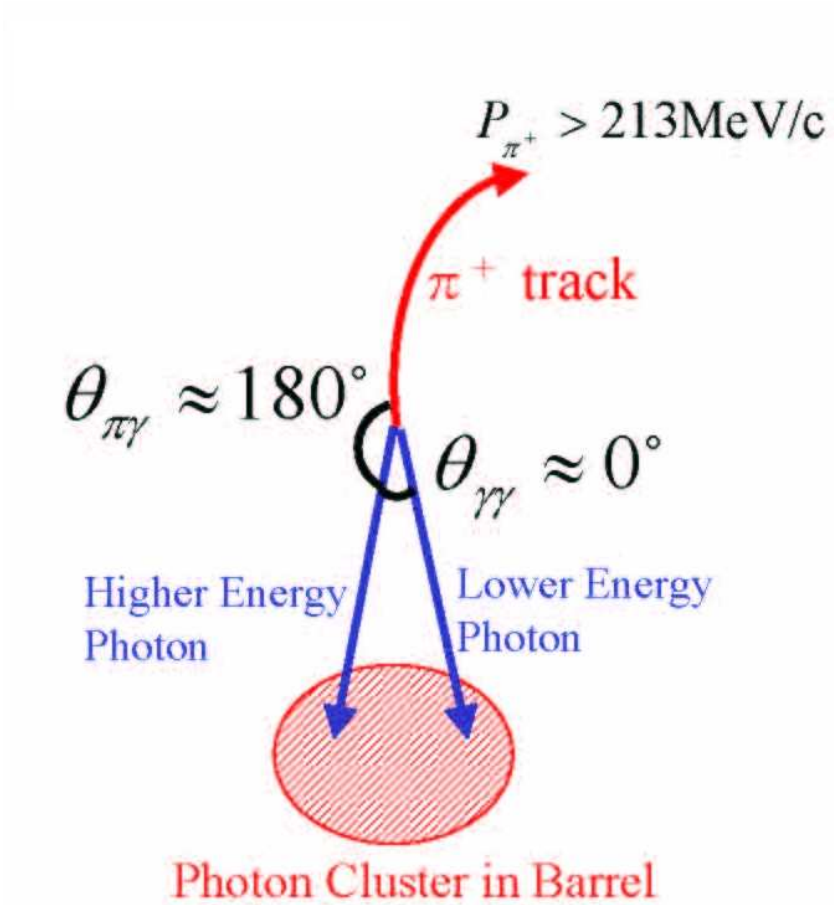


- $K_{\pi 2}$ "mismeasured"
- "muons":
  - $\mu^+\nu\gamma$, $\mu^+\pi^0\nu$,
  - $K_{\pi 2}$ with π^+ decay in flight
- $K_{\pi 2}$ decay-in-flight

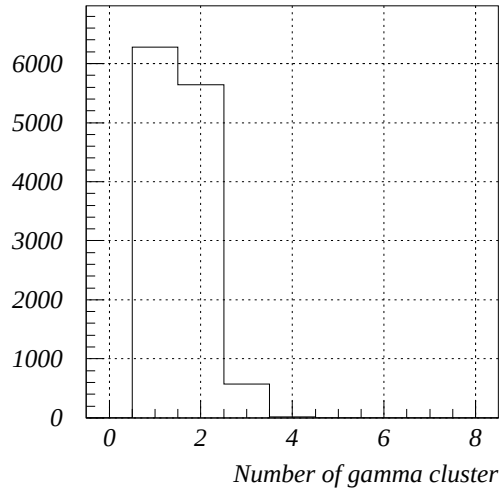
event reconstruction (w/o $K^+ \to \pi^+\gamma\gamma$ kinematic fit)

π^+ search region ("box")

- $213 < P < 234$ MeV/c
- $33.5 < R < 41.3$ cm
- $116 < E < 135$ MeV



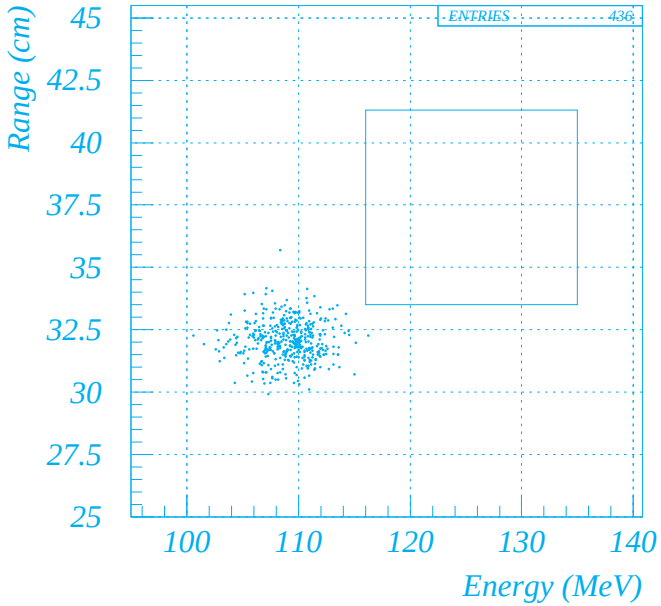
also used to the $K^+ \to \pi^+\gamma$ search

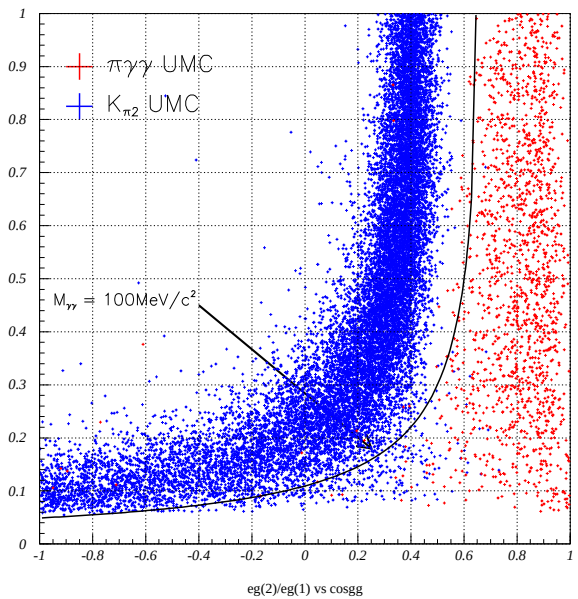


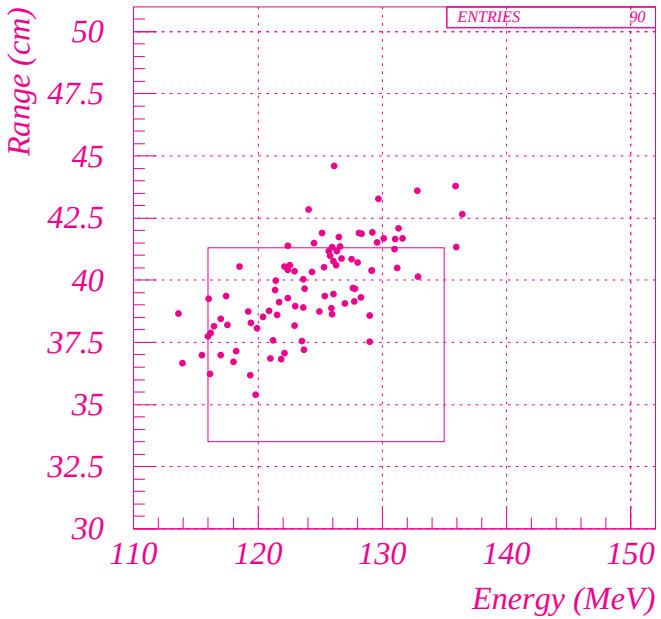
γ search region ... loose

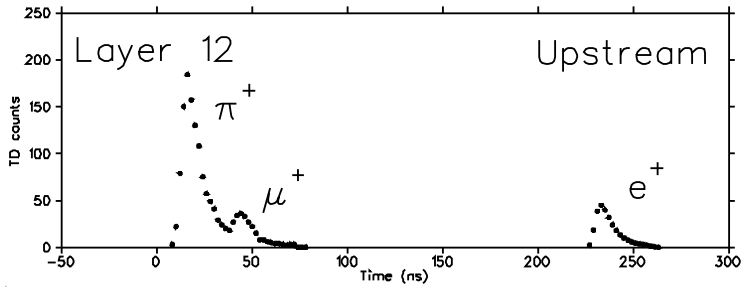
- either one or two clusters
- $50 < E_\gamma < 320$ MeV
- $\theta_{\pi+\gamma} > 155°$ (side view)
  $\phi_{\pi+\gamma} > 155°$ (end view)
- to the lower energy photon,
  $E_\gamma > 10$ MeV

backgrounds: $K_{\pi 2}$ "mismeasured", "muons"



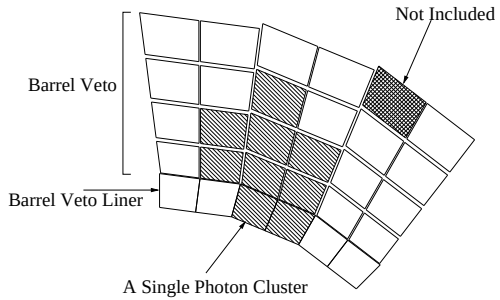


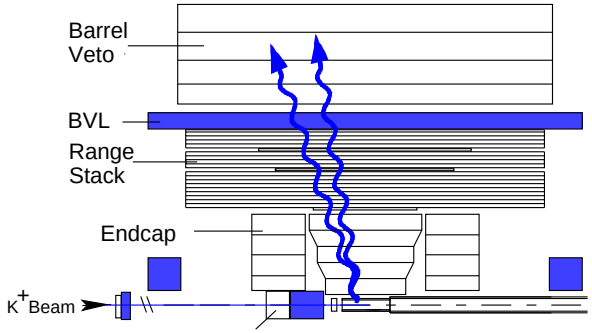


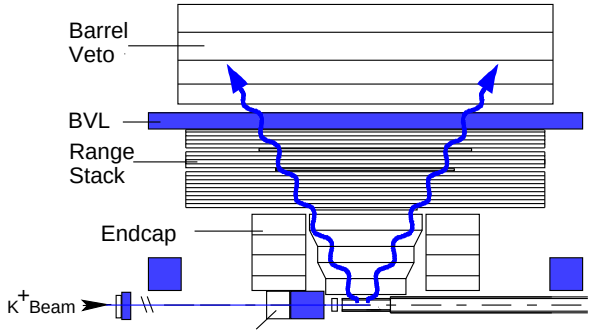


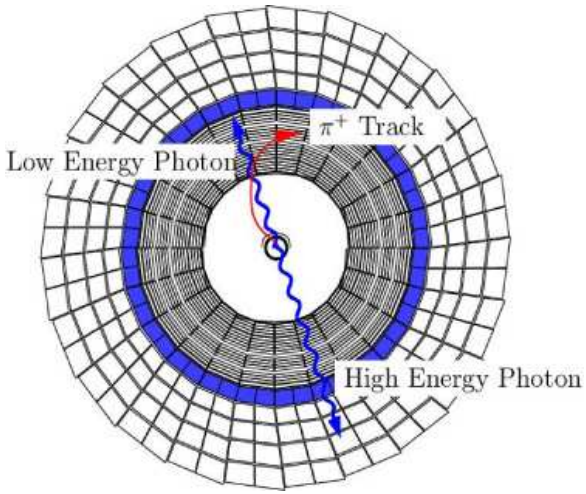
tricky $K_{\pi 2}$ background

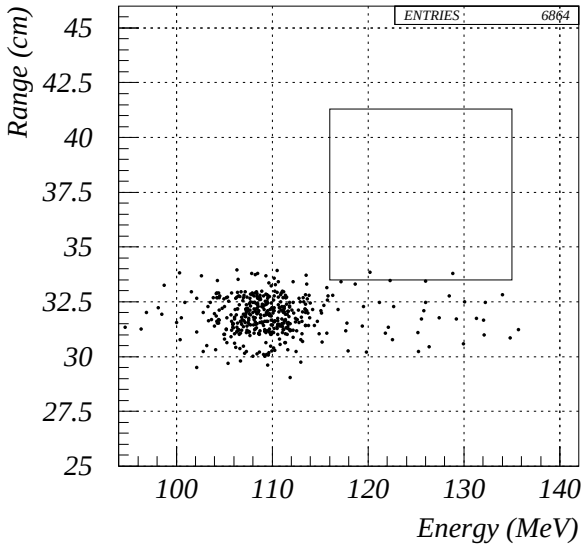
two photons into an "unresolved" single cluster

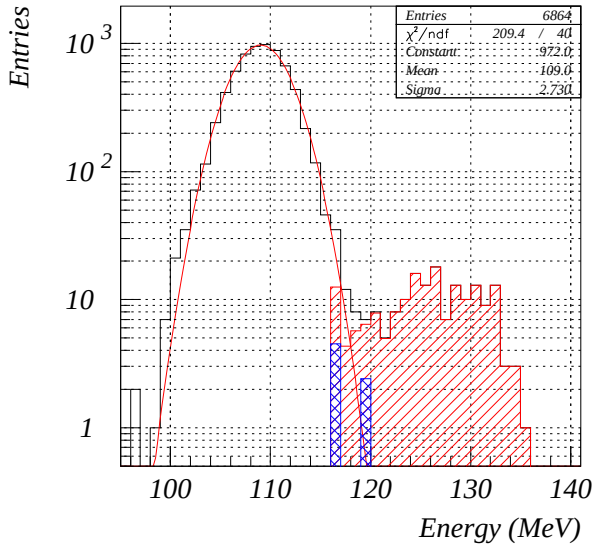












"overlap" background

E949's analysis policy and procedures

1. To avoid bias due to small statistics,
   - 1/3 of sample: for study
   - 2/3 of sample: (keep untouched)
2. study cuts for Bgd rejection with 1/3 sample, in "Blind Analysis"
3. Measure the Bgd levels in the search region with the remaining 2/3 sample. The cut points are frozen at this stage.
4. Correlation studies
5. Signal acceptance and Bgd levels, as a function of cut severity, for "Likelihood analysis" to the candidate events in the search region.
6. rehearsal with "just-outside" the search region

$\Longrightarrow$ G. Redlinger's $\pi^+\nu\bar{\nu}$ talk tomorrow

Background levels in the search region

- The total background was 0.197 ± 0.070

Source	background level	two sets of cuts	
$mismeasured$	0.017 ± 0.006	π^+ search region (P,R,E)	γ selection
$overlap$	0.065 ± 0.065	π^+ search region (P,R)	π^+ dE/dx
$muon$	0.090 ± 0.020	π^+ search region (P,R,E) π^+ range-momentum relation	$\pi^+ \to \mu^+ \to e^+$
DIF	0.025 ± 0.014	delay in the target	RS - Č timing

Acceptance and Sensitivity in the Search region

	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

Remarks before opning the box

1. a factor of 8 improvement in the sensitivity over E787.
2. The expectation is 1.6 signal events (with 0.2 backgrounds) if the ChPT including unitarity corrections $\hat{c} = 1.8$ is correct.
   - We originally designed the trigger for $\pi^+\gamma\gamma$ giving an expectation of $4 \sim 5$ signal events.
   - However, in the offline analysis, we realized that tight π^+ identification cuts should be imposed to control the muon backround.
3. E949 did not set the trigger for $\pi^+\gamma\gamma$ in $100 < P_{\pi^+} < 180$ MeV$/c$ (large $M_{\gamma\gamma}$); no new results would come from E949.

Opening the box

Range (cm) *vs* Energy (MeV)
for E949 data
after all other cuts imposed.

MC simulation:
ChPT including unitarity corrections

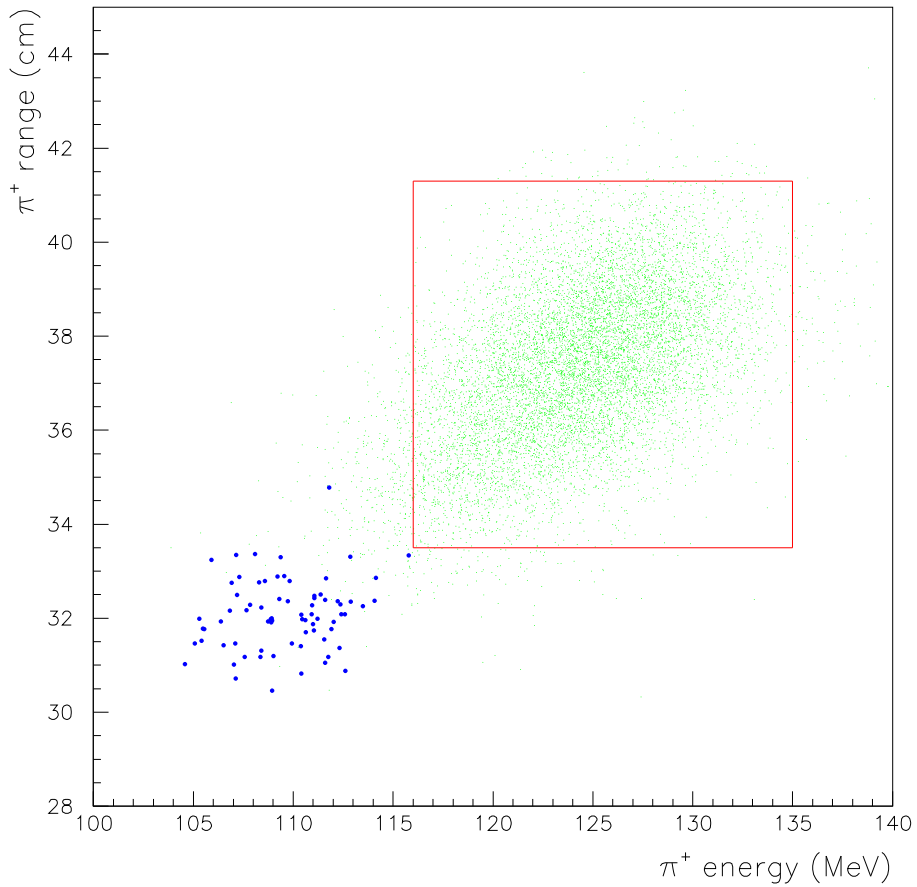
Solid line: Search region.

No events were observed.

74 events near 110 MeV:
background from $K^+ \to \pi^+\pi^0$.

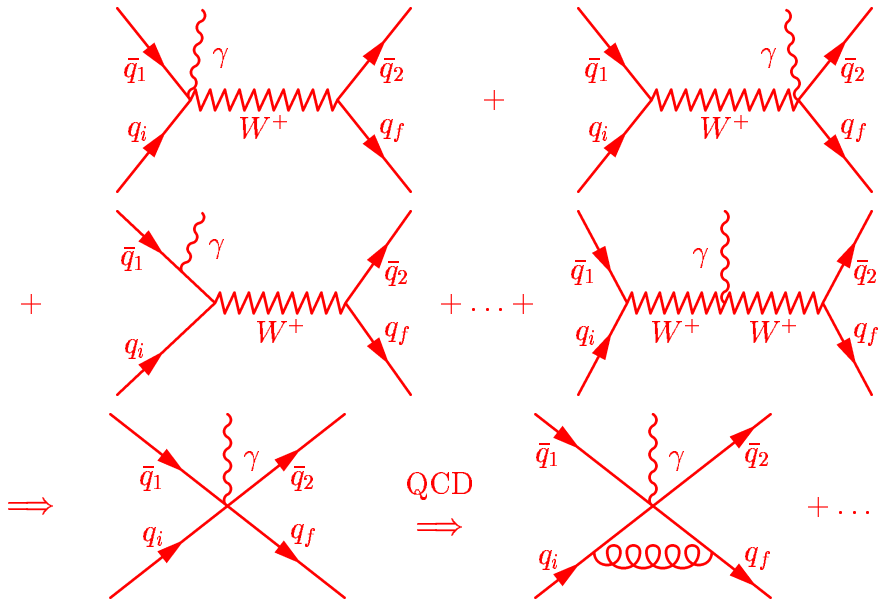
90% C.L. upper limit:

- including unitarity corrections:
  $8.3 \times 10^{-9} \quad \hat{c} = 1.8$
- without the corrections:
  $2.3 \times 10^{-8} \quad \hat{c} = 1.6$



Improved upper limit for the $K^+ \to \pi^+\gamma$ decay

- spin 0→0 transition with a real photon, forbidden by
  - angular-momentum conservation
  - gauge invariance
- a playground of "exotic" physics:
  departure from Lorentz invariance, nonlocal Superstring effects, ..
- noncommutative theories: photon does not act as the U(1) gauge boson

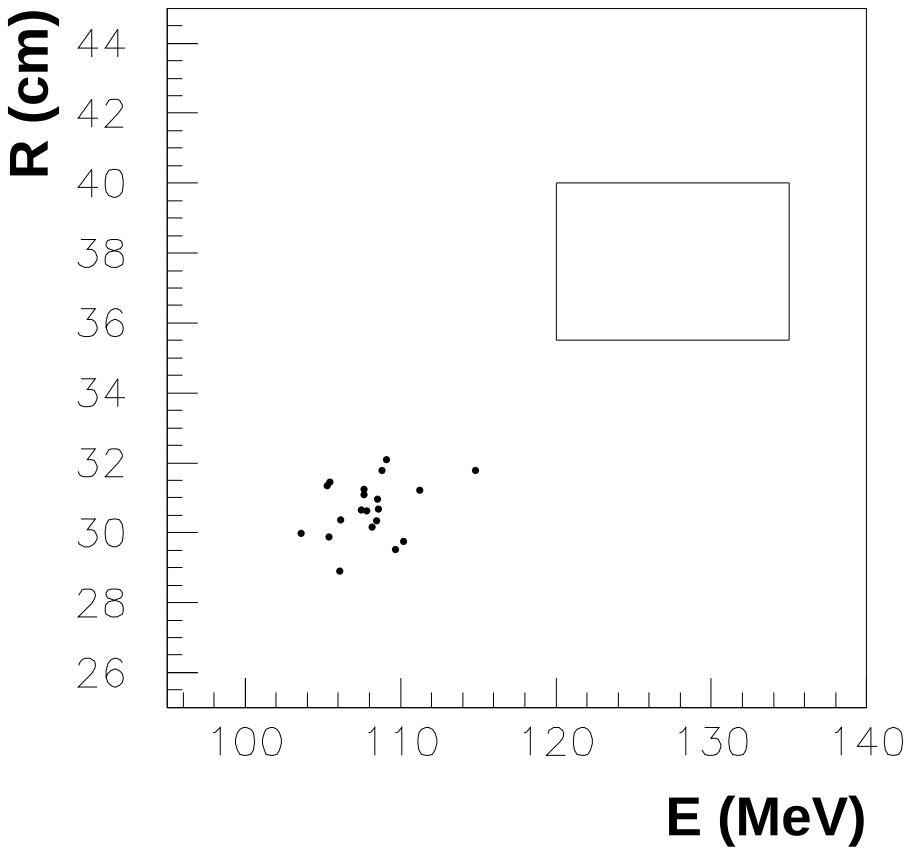


noncommutative scale Λ_{NC}

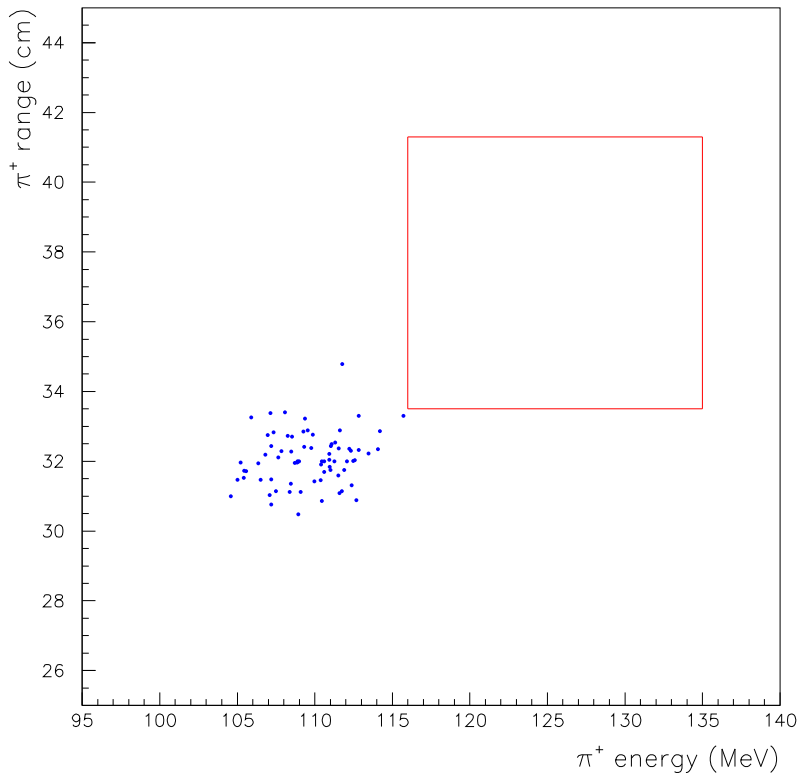
$B(Z \to \gamma\gamma) < 5.2 \times 10^{-5}$ (LEP)
$\to \Lambda_{NC} > 118$ GeV
$\longrightarrow B(K^+ \to \pi^+\gamma) < 1 \times 10^{-13}$

$K^+ \to \pi^+\gamma$: π^+ (227 MeV/c) and γ (227MeV) to the opposite sides

E787 in 1996-97 (RS layers 11–18)



E949 in 2002 (RS layers 16,17)



- prescaled by 2450, $N_K = 6.7 \times 10^8$
- 90%C.L. upper limit 3.6×10^{-7}

PRD 65 (2002) 052009

- $N_K = 1.19 \times 10^{12}$
- 90%C.L. upper limit $\underline{2.3 \times 10^{-9}}$

also in hep-ex/0505069

Conclusions

- $\mathbf{K}^+ \to \boldsymbol{\pi}^+\boldsymbol{\gamma}\boldsymbol{\gamma}$ in the region $P_{\pi^+} > 213$ MeV/c is sensitive to the NLO "unitarity" corrections of ChPT.
- The results of this study cannot confirm nor rule out the unitarity corrections.
- The upper limits are the most restrictive yet achieved on $\mathbf{K}^+ \to \boldsymbol{\pi}^+\boldsymbol{\gamma}\boldsymbol{\gamma}$ and as well as on $\mathbf{K}^+ \to \boldsymbol{\pi}^+\boldsymbol{\gamma}$.
- K^+ decays at rest are suitable for the study of $\mathbf{K}^+ \to \boldsymbol{\pi}^+\boldsymbol{\gamma}\boldsymbol{\gamma}$ (and for stringent tests of the ChPT).
- You may take an opportunity to observe the $\mathbf{K}^+ \to \boldsymbol{\pi}^+\boldsymbol{\gamma}\boldsymbol{\gamma}$ decay in the region (and, of course, the $\mathbf{K}^+ \to \boldsymbol{\pi}^+\boldsymbol{\gamma}$ decay) in future !

BNL E949 collaboration

~ 60 physicists, 15 institutes from Canada, Japan, Russia and the US.

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backup slides

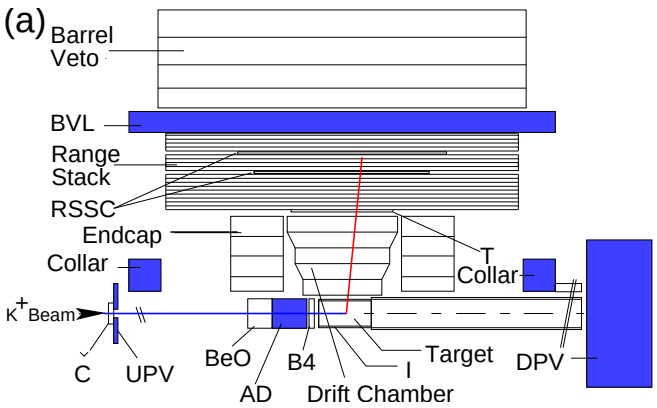
Reminder: E949-2002 beam conditions were not optimized

- a failure of the AGS power supply
- reduced operating voltage of one of the DC separators
- 12 weeks

The conditions will be improved in the next run.

		E787	E949-'02	E949 optimized
AGS energy	GeV	24	22	24
beam spill	sec	2.2	2.2	4.1
cycle	sec	4.2	5.4	6.4
duty factor	%	52	41	64
K^+/π^+		4	3	4
N_K in the spill	M	1.8	2.5	5.0
N_K	MHz	0.8	1.2	1.2
rates in the detector			$\times 2$	$\times 2$ or less
beam time	weeks		12	$\geq$60

E949 upgrades (2): Rate capability, Kinematics

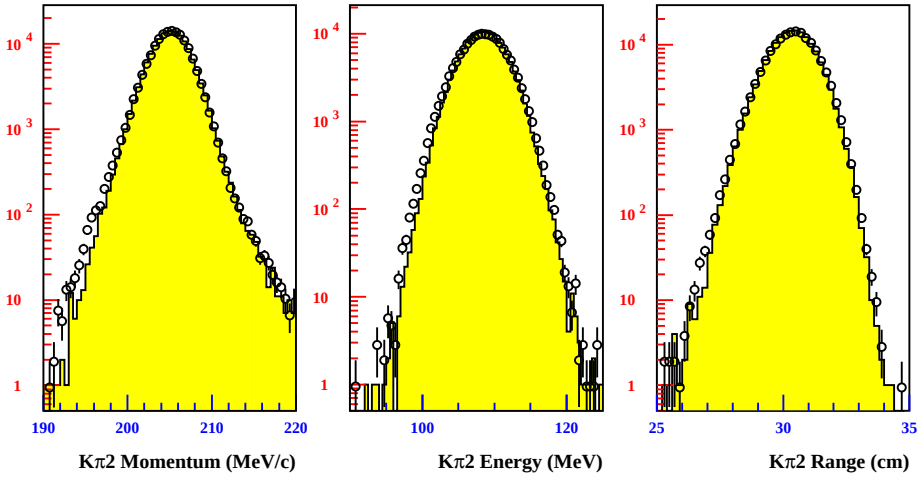


- higher segmented B4 hodoscope
- record waveforms from beam counters
- RS Layer 1-5, 19 replaced
  $\longrightarrow$ more light output
- LED flasher system $\longrightarrow$ RS monitor
- new wire-chamber electronics

π^+ kinematics from $K_{\pi 2}$:
E787(○) vs E949 (histo)

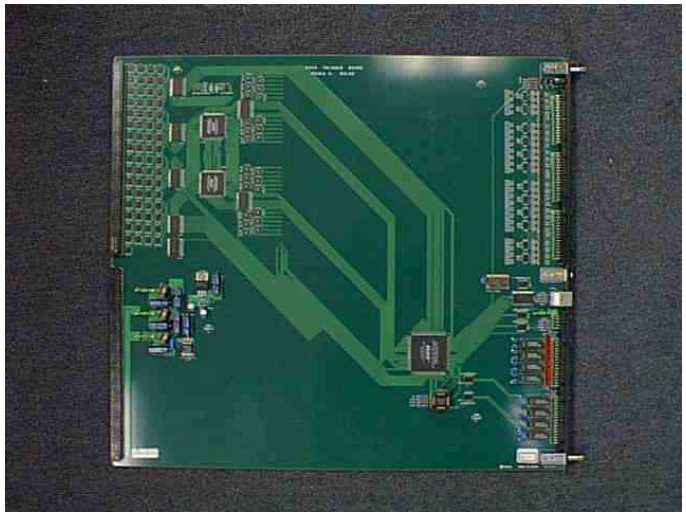
- $\sigma_P = 2.3$ MeV/c
- $\sigma_E = 3.0$ MeV
- $\sigma_R = 0.9$ cm

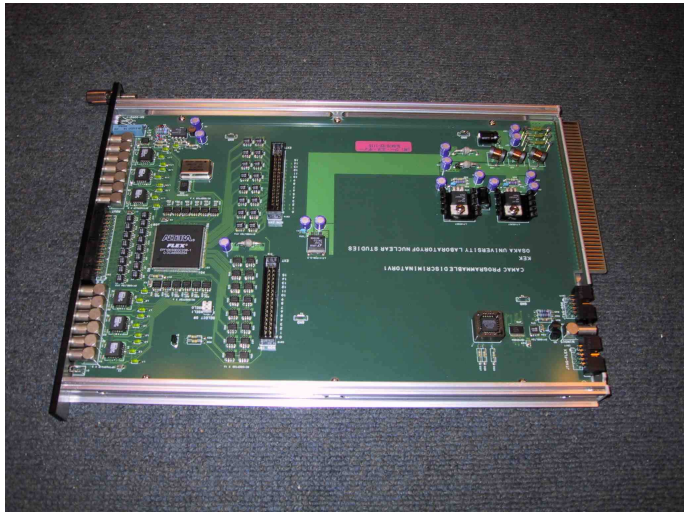
Reminder:
the rate is $\times 2$ higher in E949.

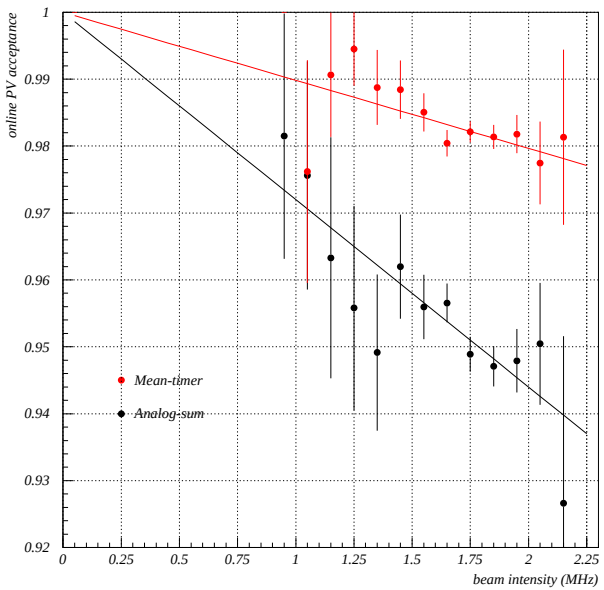


E949 upgrades (3): Trigger/DAQ

e.g. Level0 trigger board and digital Meantimer module

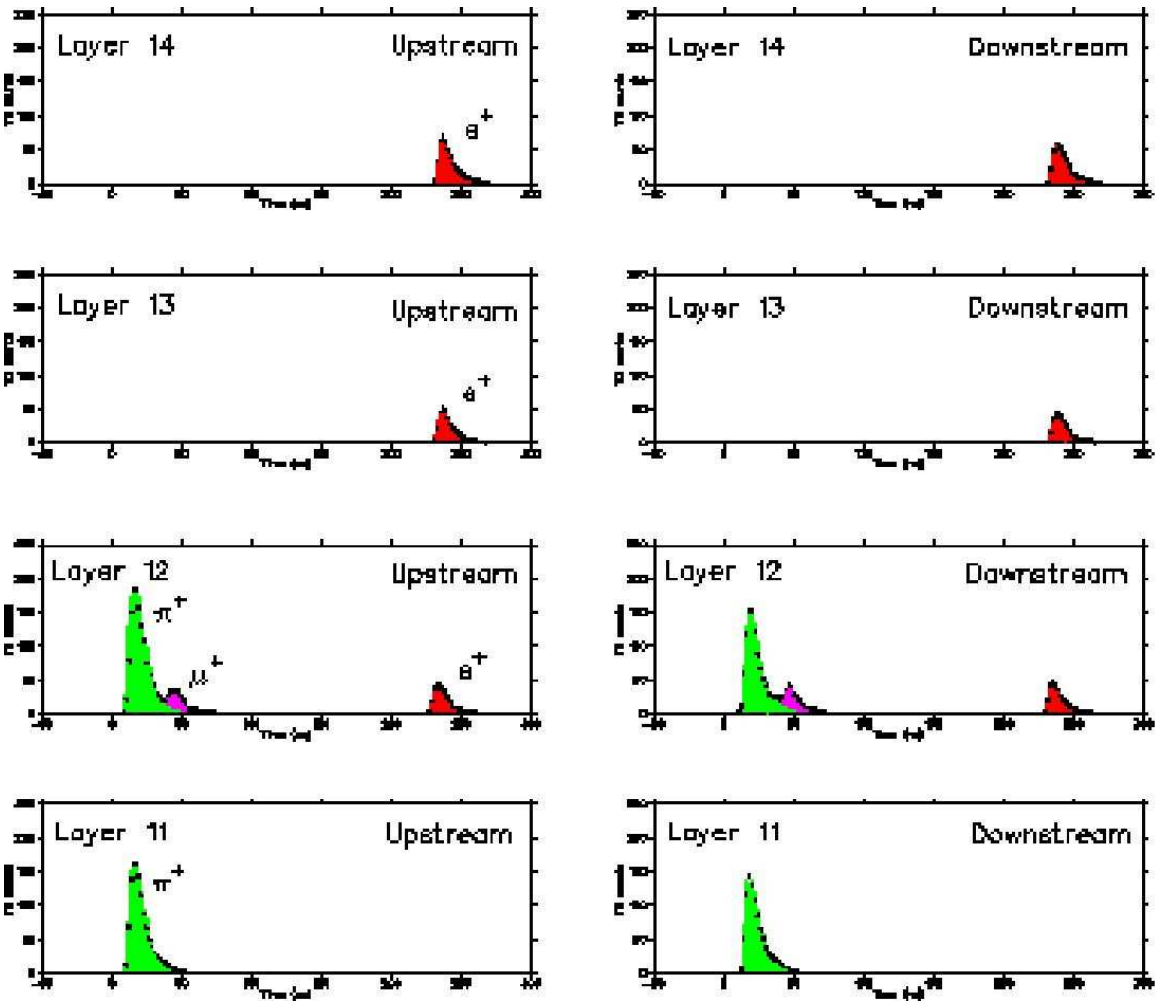






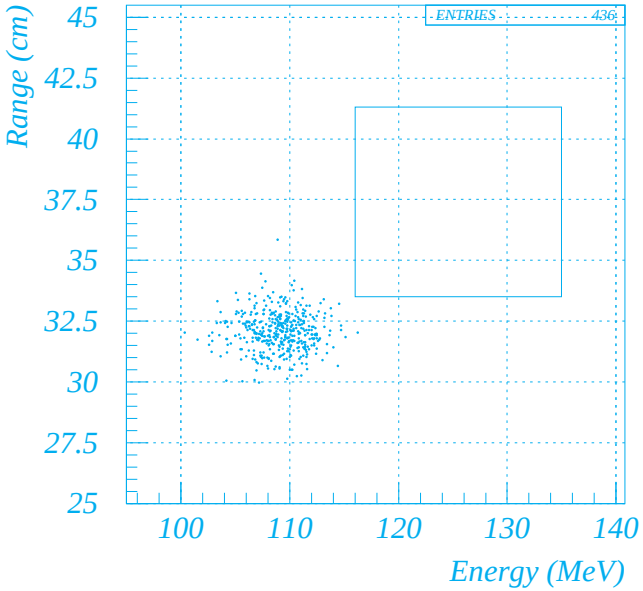
T.Yoshioka, M.Nomachi et al., IEEE TNS 51 (2004) 334

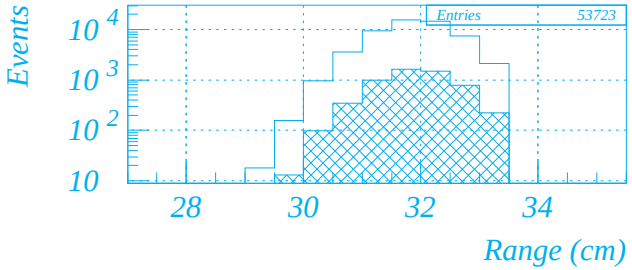
$\pi^+ \to \mu^+ \to e^+$ recorded by 500-MHz waveform digitizer

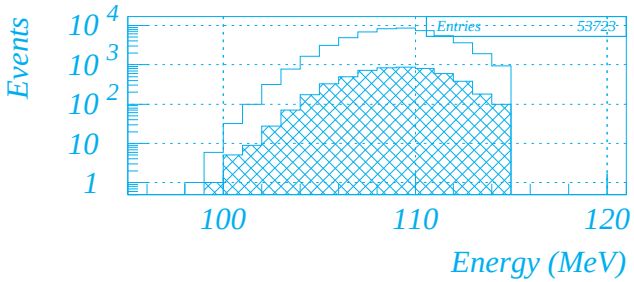


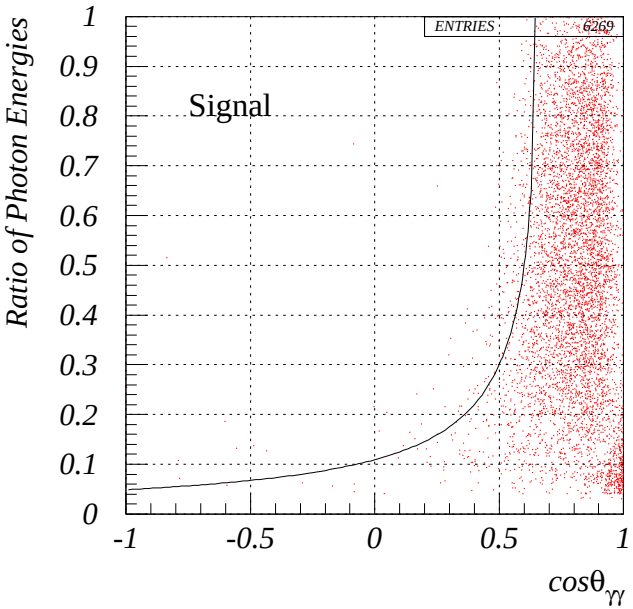
Online + Offline μ^+ rejection ($> 10^5$)

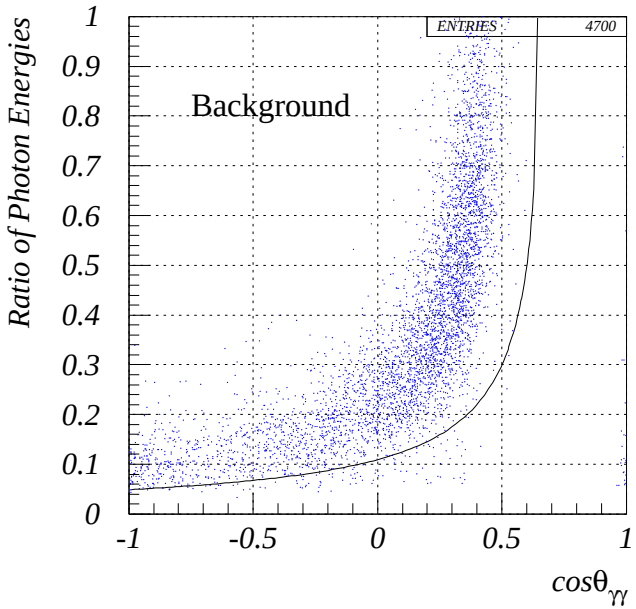
backgrounds: $K_{\pi 2}$ "mismeasured"



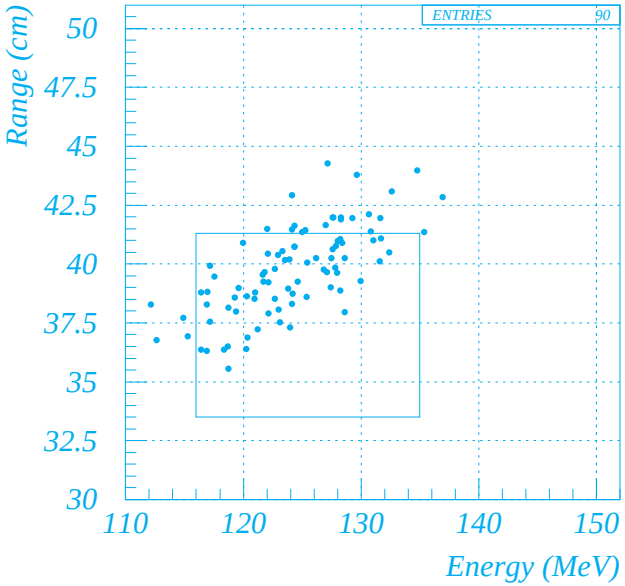


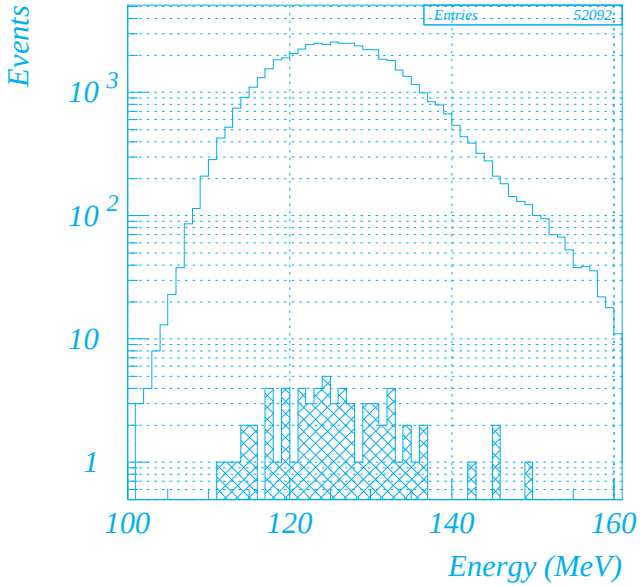


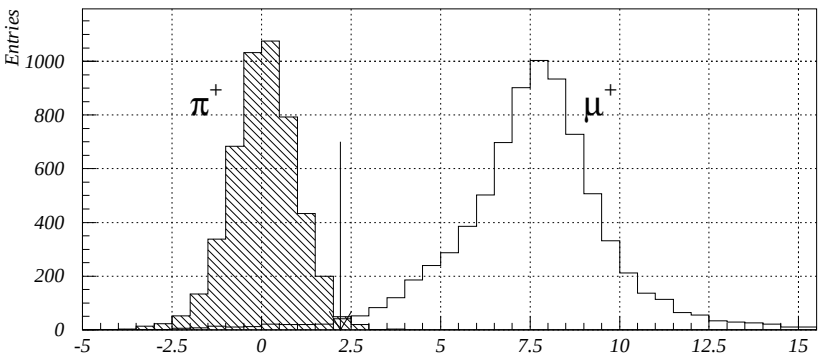


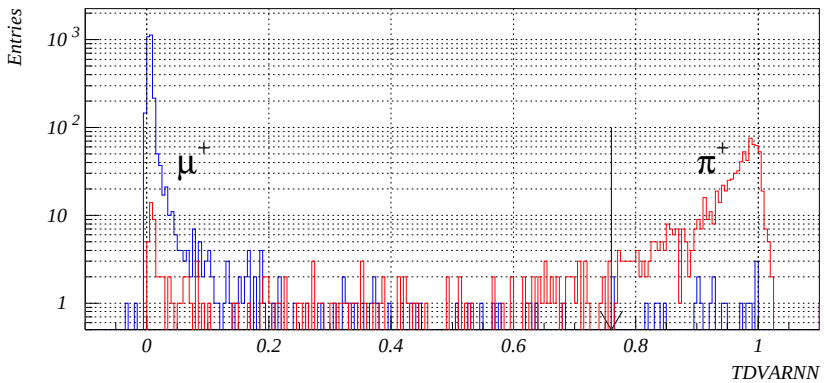


backgrounds: “muon”

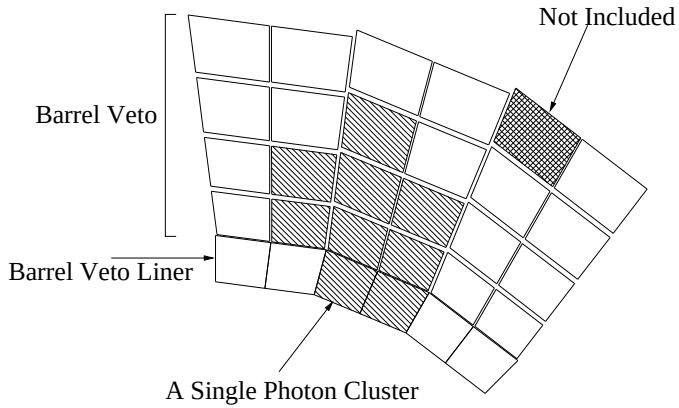


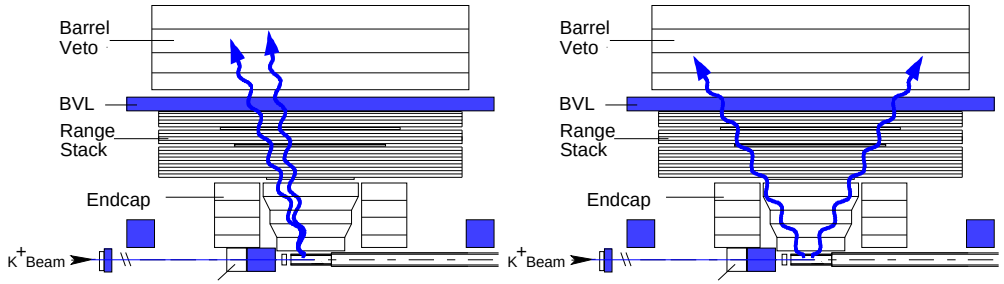


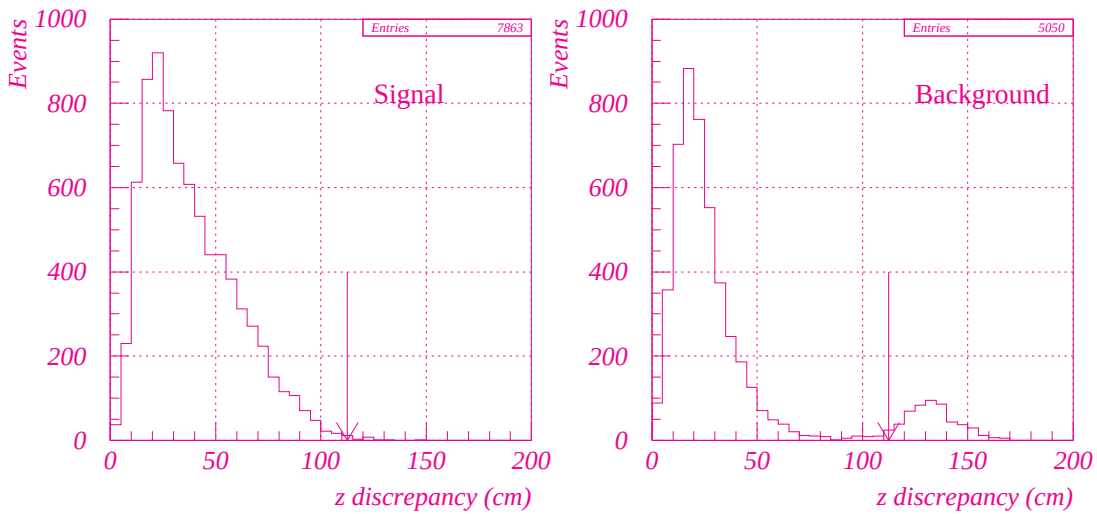




$K_{\pi 2}$ with two photons into an "unresolved" single cluster







Acceptance

Acceptance factors	UC	w/o UC	samples
Trigger ($P_{\pi^+} > 213$ MeV/c)	0.0623	0.0407	MC, K_B
π^+ reconstruction and fiducial cuts	0.980	0.935	MC, $K_{\mu 2}$
π^+ search region (P,R,E)	0.912	0.667	MC
π^+ stop without nuclear interaction or decay-in-flight	0.492	0.524	MC
dE/dx and kinematic cuts	0.537	0.537	$K_{\pi 2}$, π_{scat}
$\pi^+ \to \mu^+ \to e^+$ cuts	0.349	0.349	π_{scat}
γ reconstruction and fiducial cuts	0.530	0.492	MC, $K_{\pi 2}$
γ selection cuts	0.216	0.177	MC, $K_{\pi 2}$
Other cuts on beam and target	0.507	0.507	$K_{\mu 2}$
Total acceptance	2.99×10^{-4}	1.10×10^{-4}	