Recent Results from E949

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Outline

Introduce E949 detector

Report Final Results from

- $BR(K^+ \to \pi^+\pi^0\gamma)$ (Still preliminary)
- $BR(K^+ \to \pi^+\gamma\gamma)$
- $BR(K^+ \to \pi^+\gamma)$
- $BR(\pi^0 \to \nu\overline{\nu})$

Update on E949-PNN2 analysis

E949 Collaboration

UNIVERSITY OF ALBERTA
EDMONTON, ALBERTA, CANADA

UBC

INR

The University of New Mexico

BROOKHAVEN
NATIONAL LABORATORY

Fermilab

National Defense Academy, Japan

KEK

Fukui University

KYOTO UNIVERSITY
FOUNDED 1897
KYOTO JAPAN

OSAKA UNIVERSITY

TRIUMF

IHEP

STONY BROOK
STATE UNIVERSITY OF NEW YORK

E787
Princeton

E949 Collaboration

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~50 Scientists

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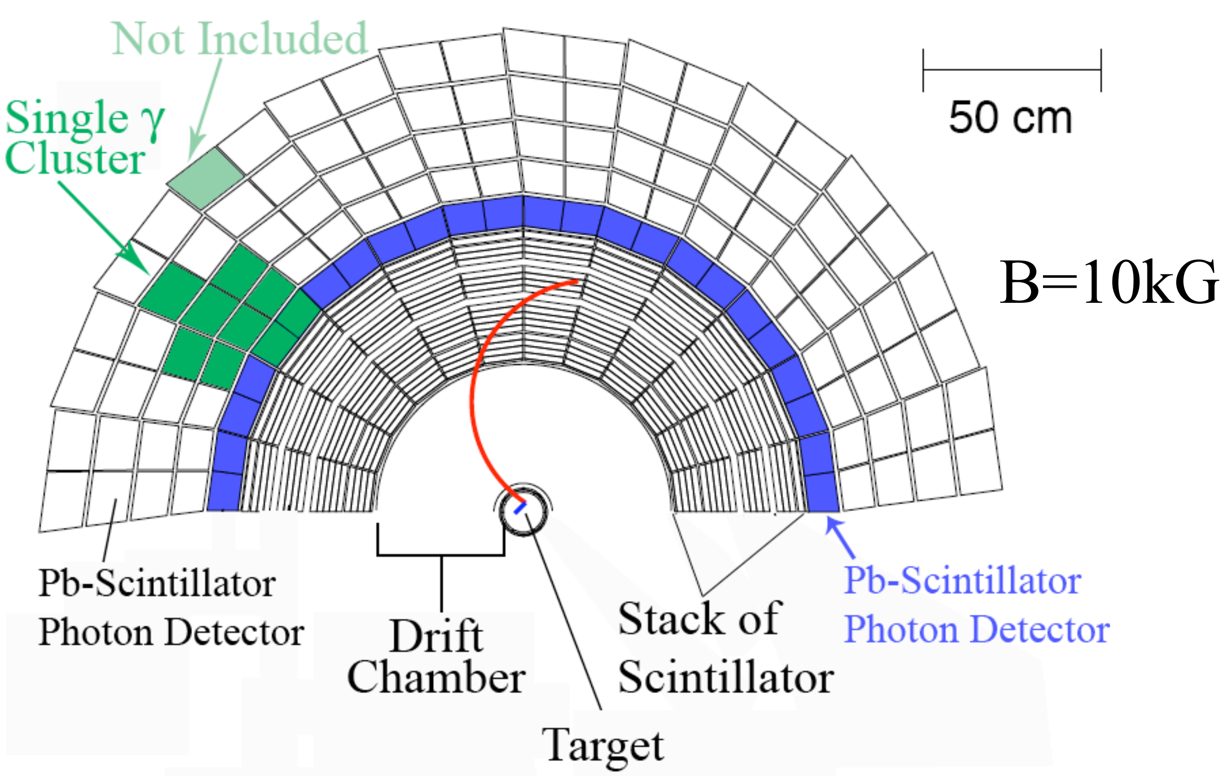
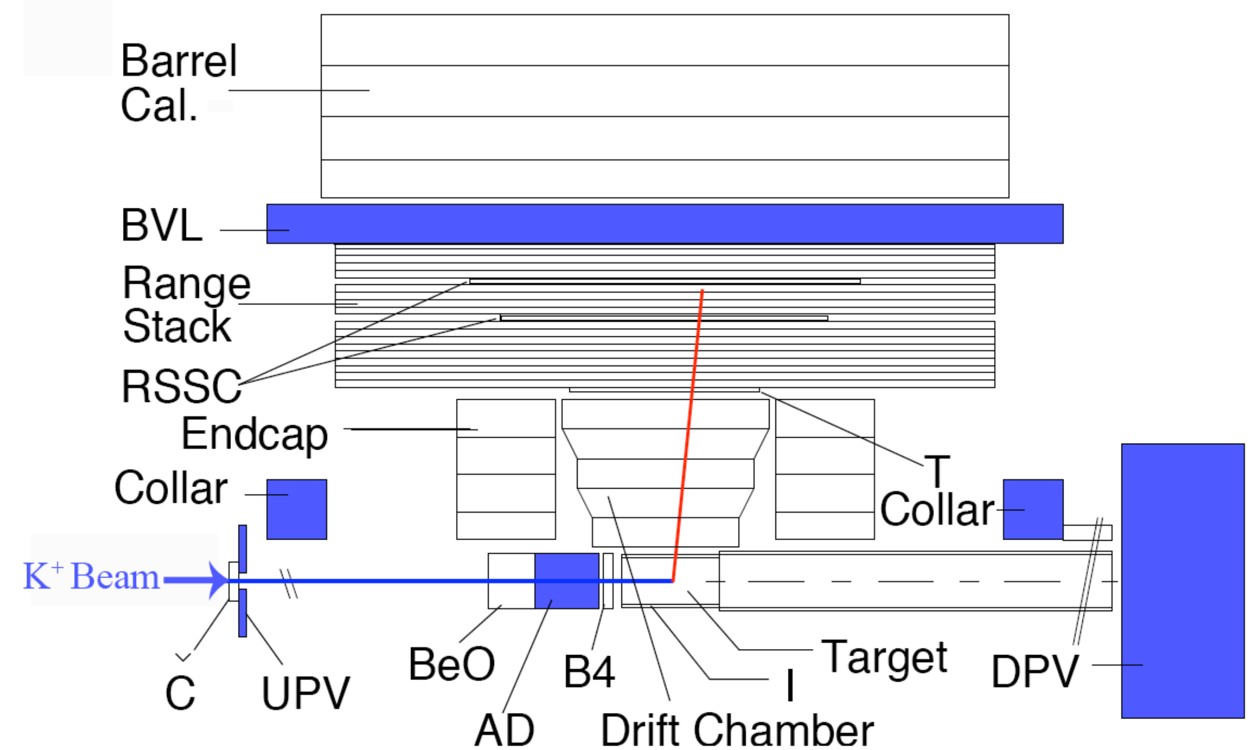
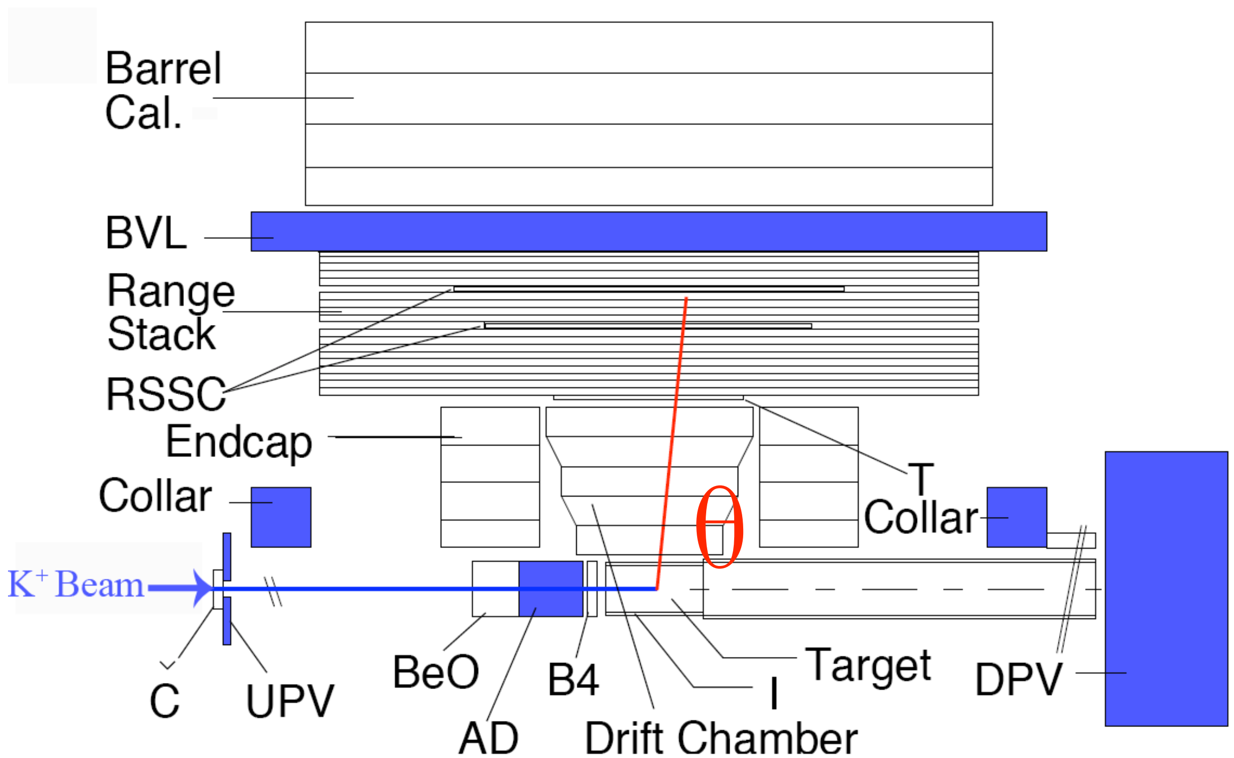
$K^+ \to \pi^+ \nu\bar{\nu}$ Detector





- Designed to measure $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ $(E949\ results)$
- Incoming K^+ beam: ~710 MeV/c, K^+/π^+ = 3/1
- Decay product: 2ns delay from K^+
- Stopped decay product: Measure *Energy, Momentum, Range*.
  - Observe $\pi^+ \to \mu^+ \to e^+$ decay sequence
- Photon detection: Everywhere possible!
- Designed for $K^+ \to \pi^+ \nu\nu$, but other decay modes accessible.

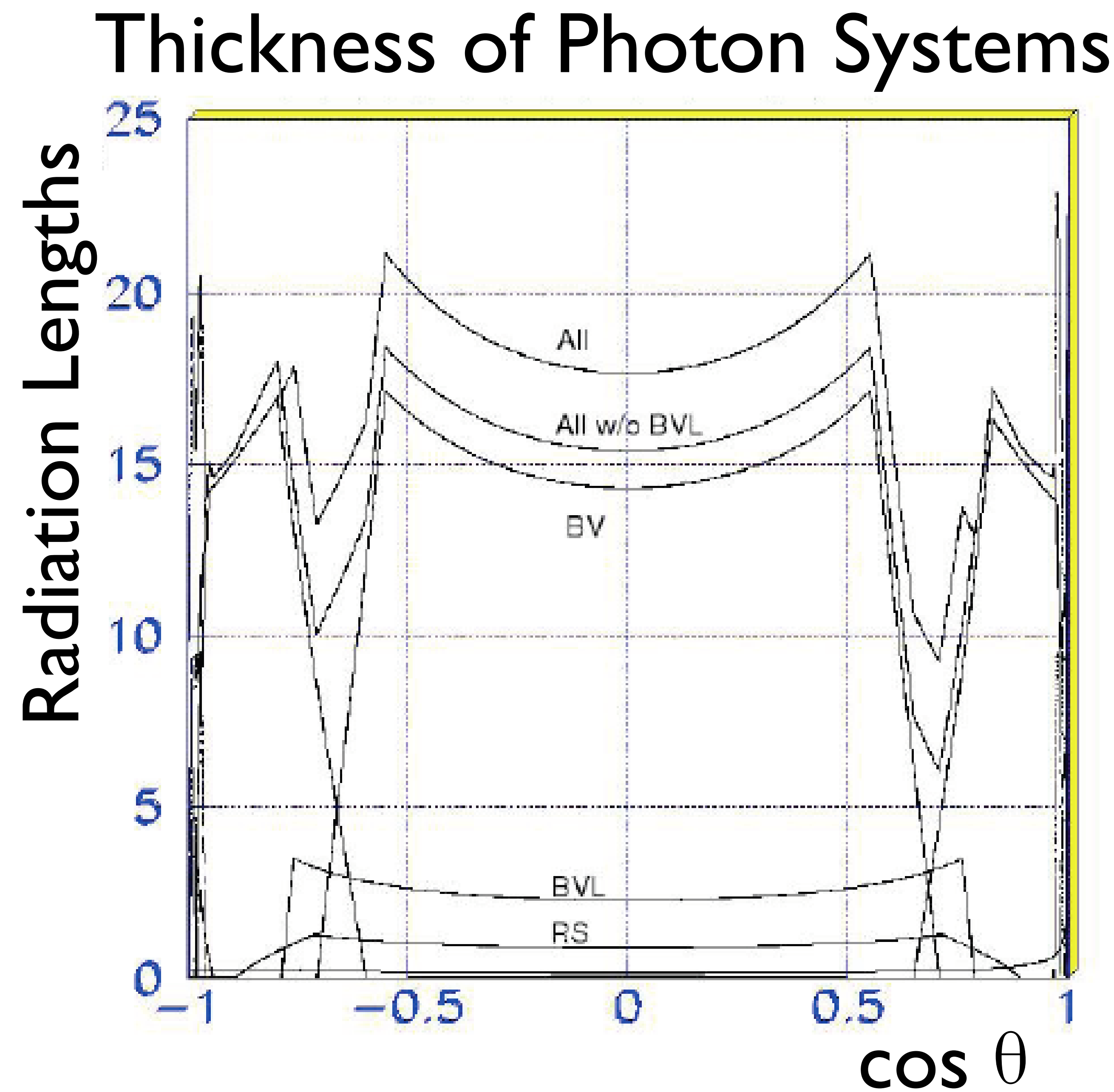
Photon Detectors



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

π^0 rejection: $\sim O(10^6)$

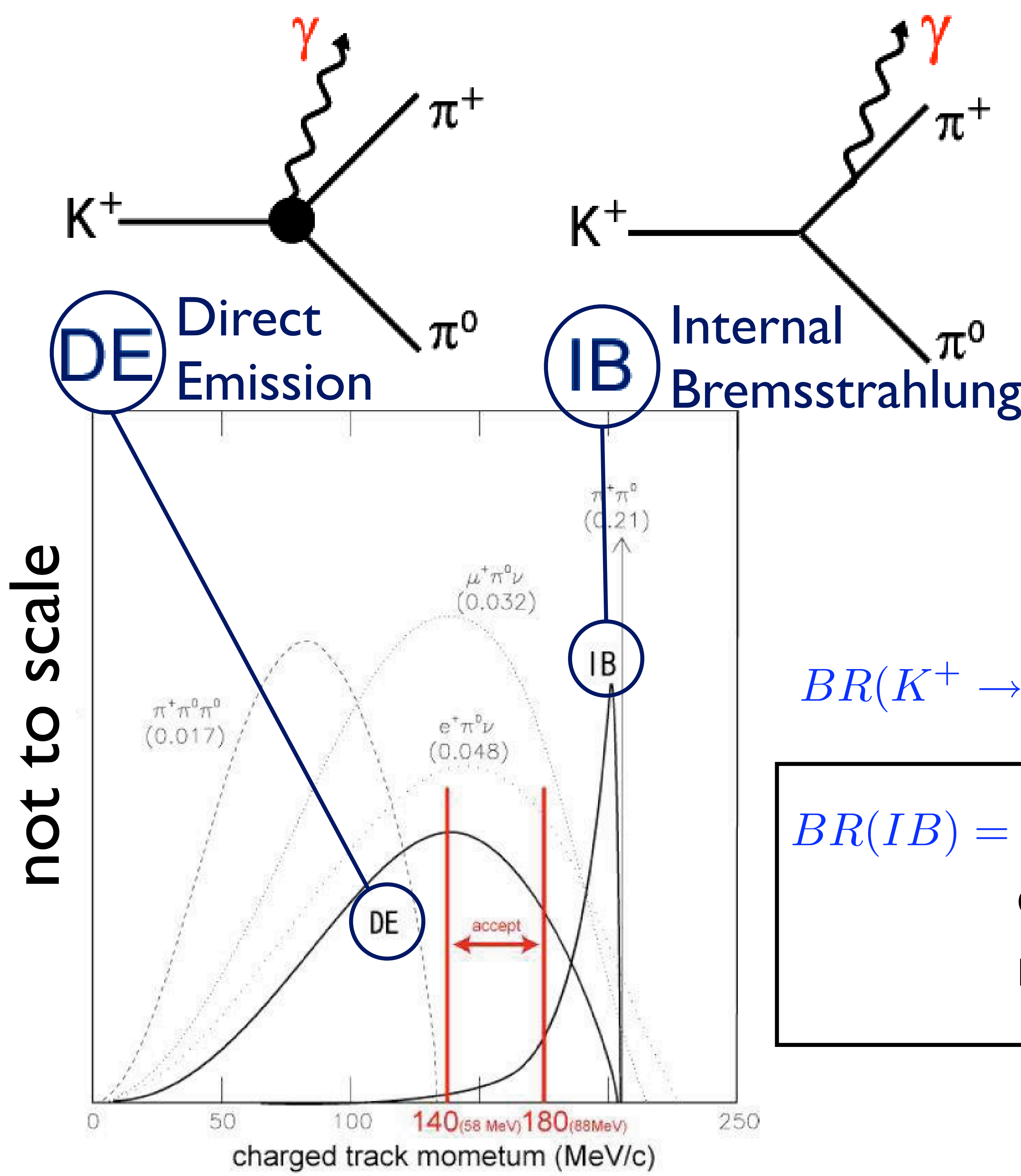
BR measurement require best photon detection possible



$K^+ \to \pi^+ \nu\nu$ has no photons, but the background $K^+ \to \pi^+ \pi^0$ has 2 photons

$K^+ \to \pi^+ \pi^0 \gamma$ has three photons in the decay products.

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



Chiral Perturbation Theory (ChPT) are not predictable about some components of the DE and must be found experimentally.

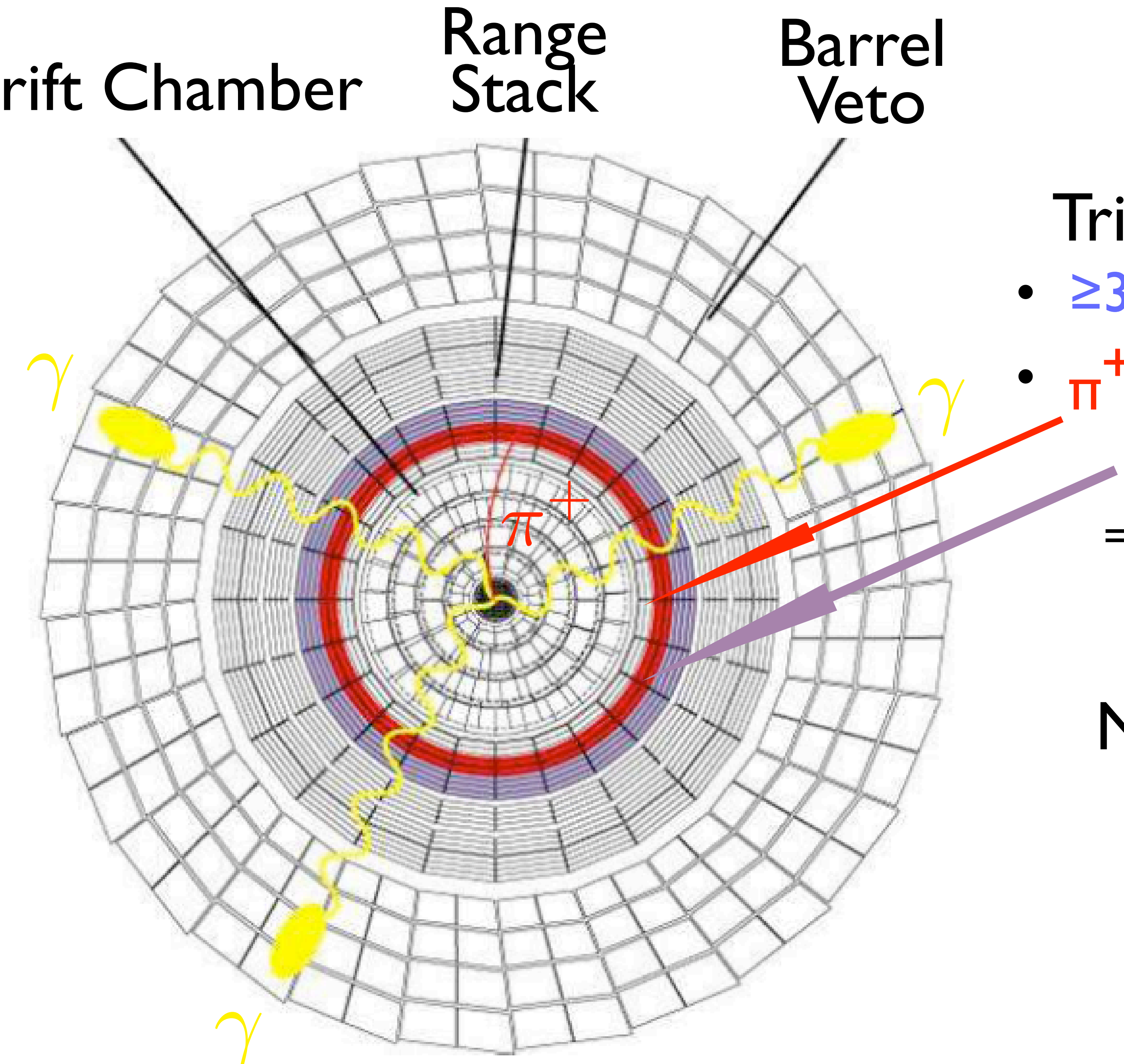
$BR(K^+ \to \pi^+\pi^0\gamma) = (2.75 \pm 0.15) \times 10^{-4} \quad (PDG04)$

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

dominates QED

radiative correction to BR($K_{\pi 2}$)

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



Trigger Requirements

- ≥3 photon clusters
- π^+ stop in RS layer 3-6 (1998)
  layers 6-10 (1995)

  ⇒ More Acceptance for DE than 1995

Number of kaons:
3.48×10^{11} (1998)
2.83×10^{11} (1995)

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

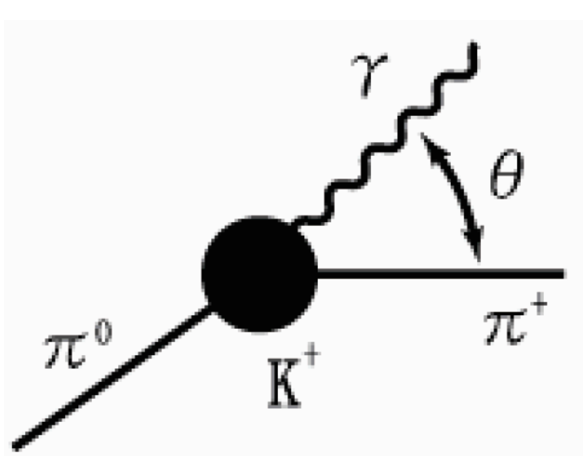
Background estimated from data using same techniques as in $K^+ \rightarrow \pi^+\nu\nu$ analyses.

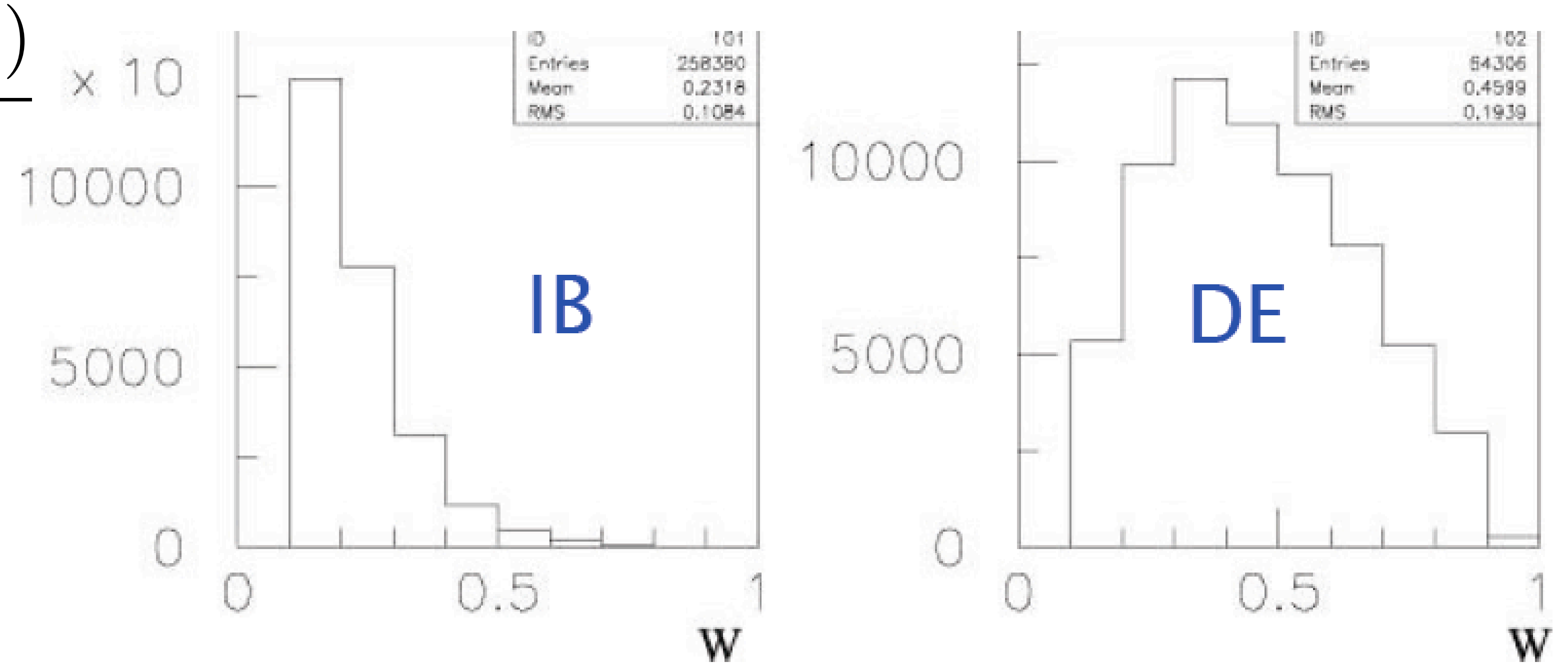
- 1.3% background in "DE region"

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

In Kaon rest frame

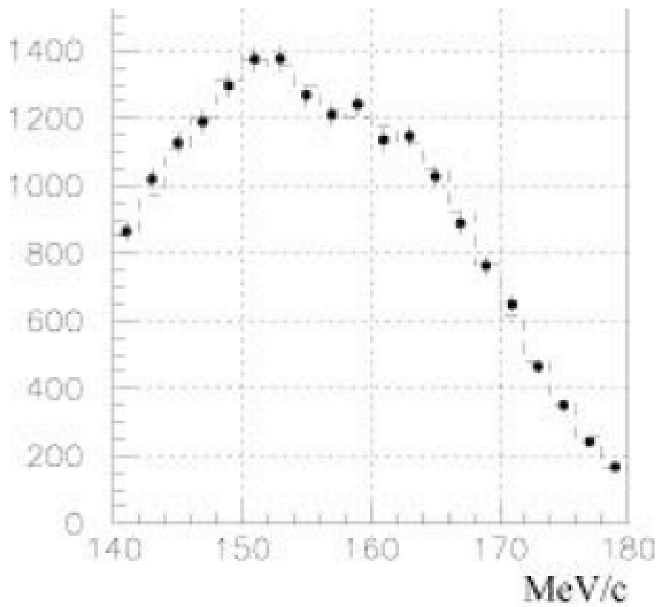
$$W^2 = \frac{E_\gamma^2 (E_{\pi^+} - P_{\pi^+} + \cos\theta_{\gamma\pi^+})}{m_K m_{\pi^+}^2}$$



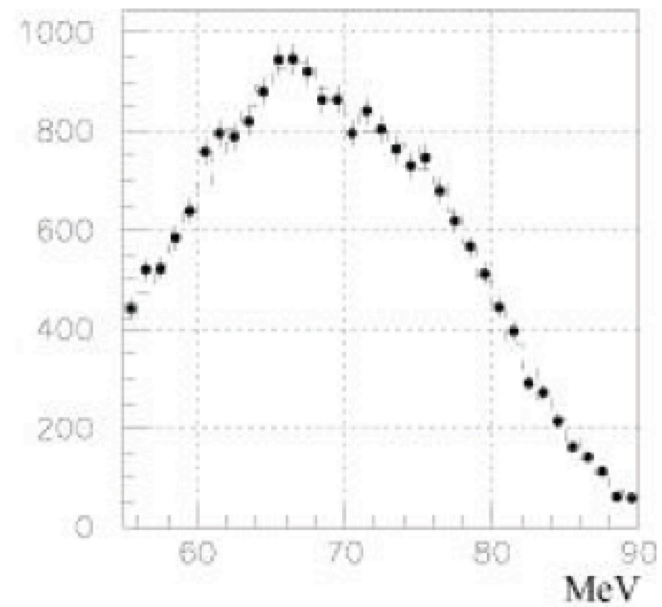


$K^+ \to \pi^+\pi^0\gamma$

Data & MC Consistency

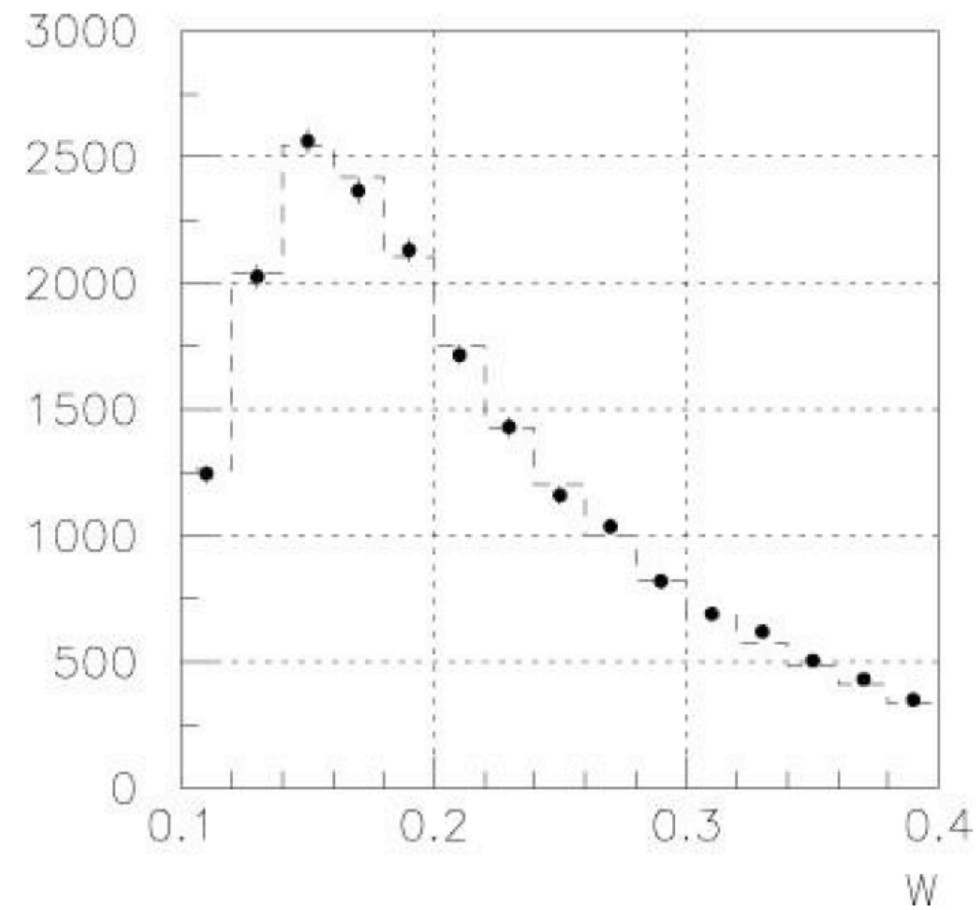


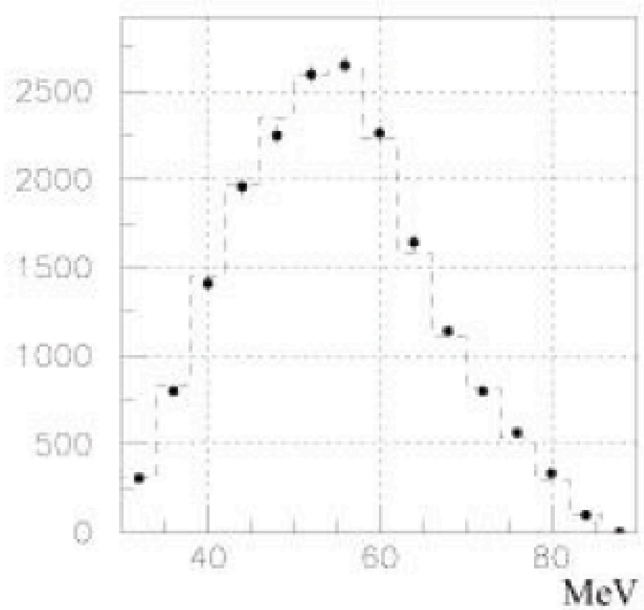
π^+ momentum



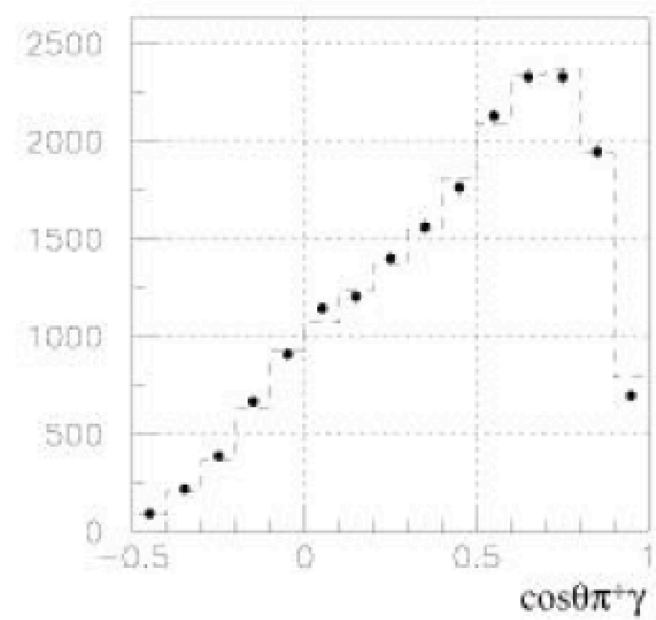
π^+ energy

Remove DE: require W<0.4





photon energy



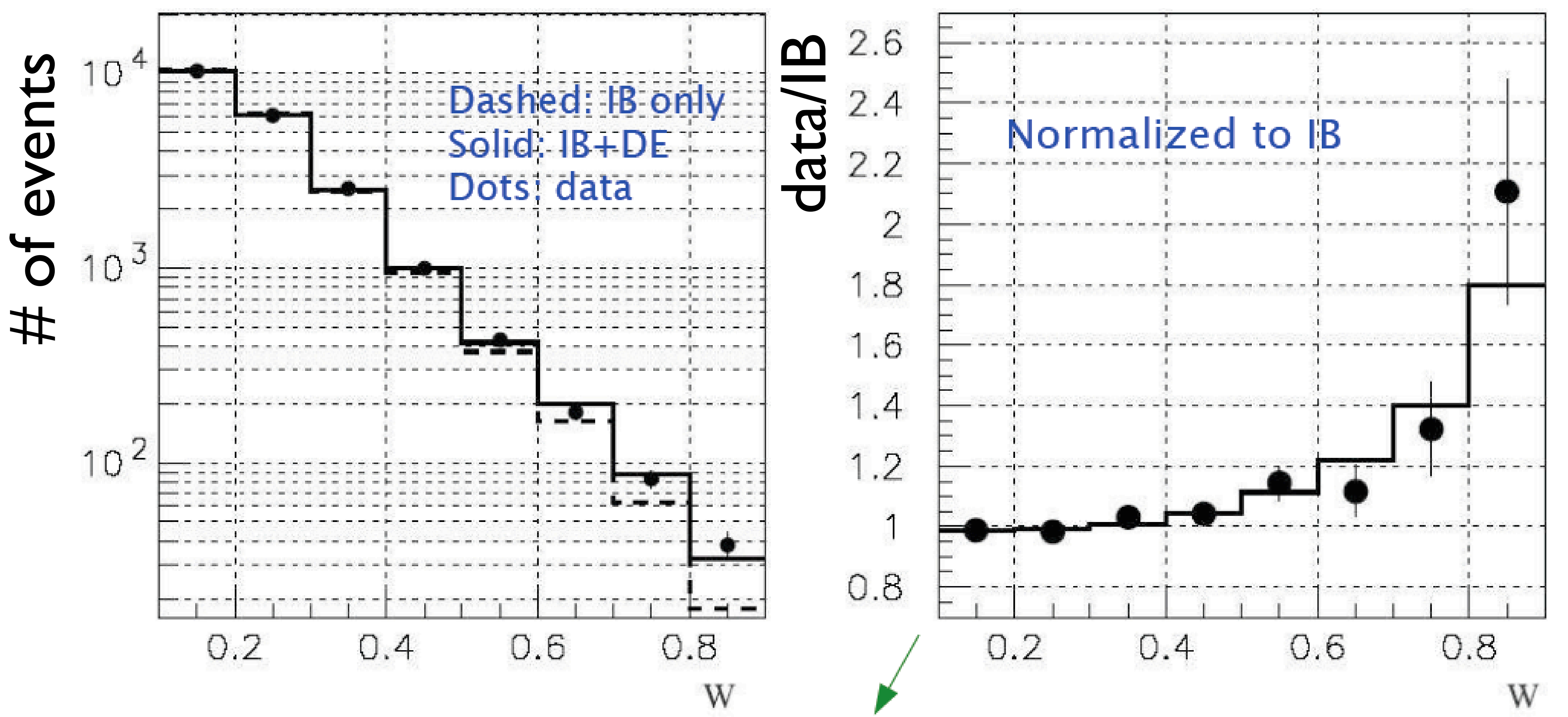
$\cos\theta_{\pi^+\gamma}$

Dots = Data

Dashed = Monte Carlo

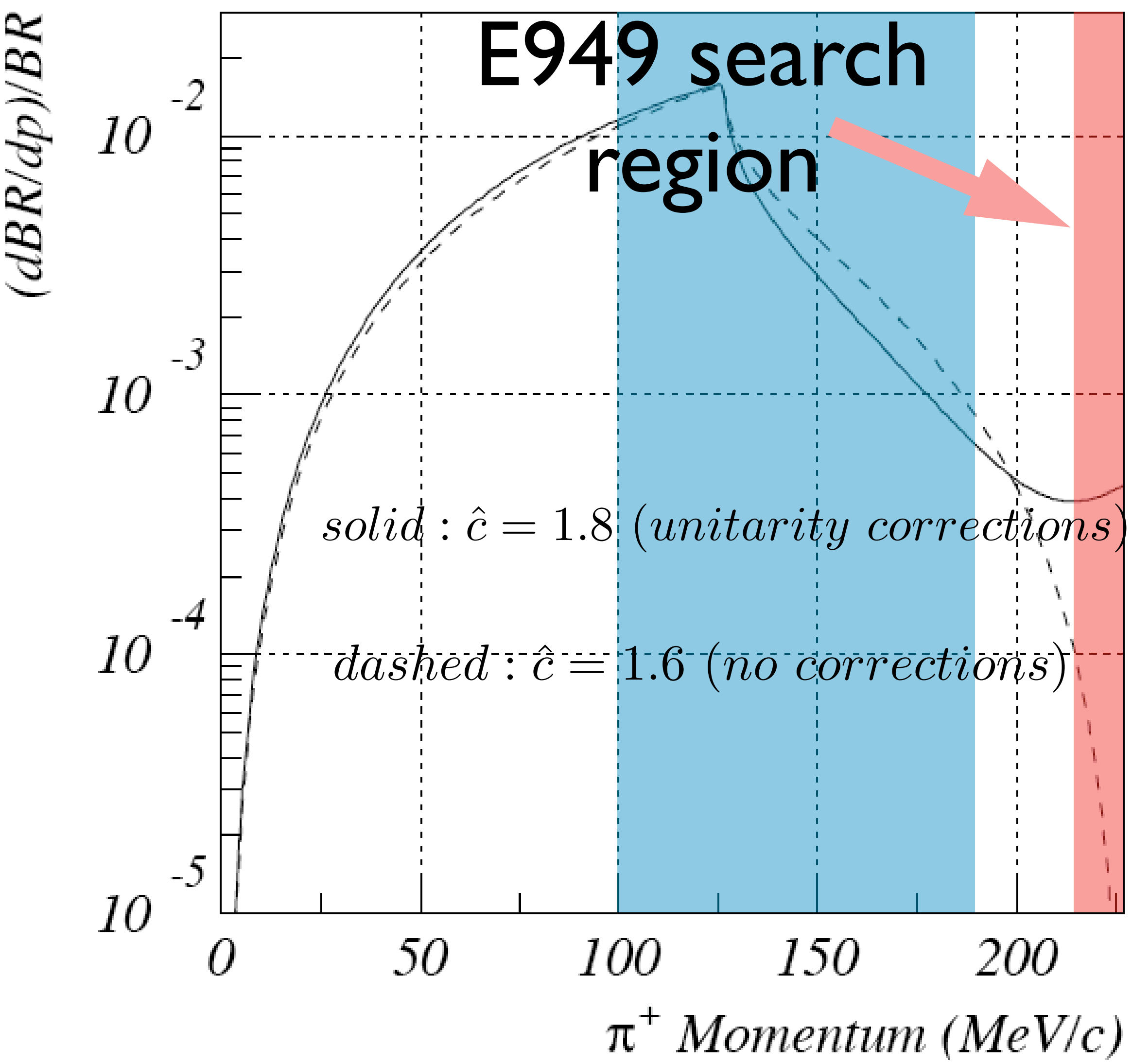
$K^+ \to \pi^+\pi^0\gamma$

W Spectrum



BR($K^+ \to \pi^+ \pi^0 \gamma$, DE, $T(\pi^+)$=(55,90) MeV) = $(3.5 \pm 0.6\ (\text{stat})\ ^{+0.3}_{-0.4}\ (\text{sys})) \times 10^{-6}$
E787 (1998 data) Preliminary.

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



- $O(p^4)$ in Chiral Perturbation Theory (ChPT), BR & spectrum shape depend on ĉ parameter.
- Unitarity Corrections (UC) dominate at $O(p^6)$.
  - E787 slightly preferred UC.
-
- Finite BR at kinematic end point using UC.
  - Dramatic difference >200 MeV/c
  - Ideal region for E949 to attack

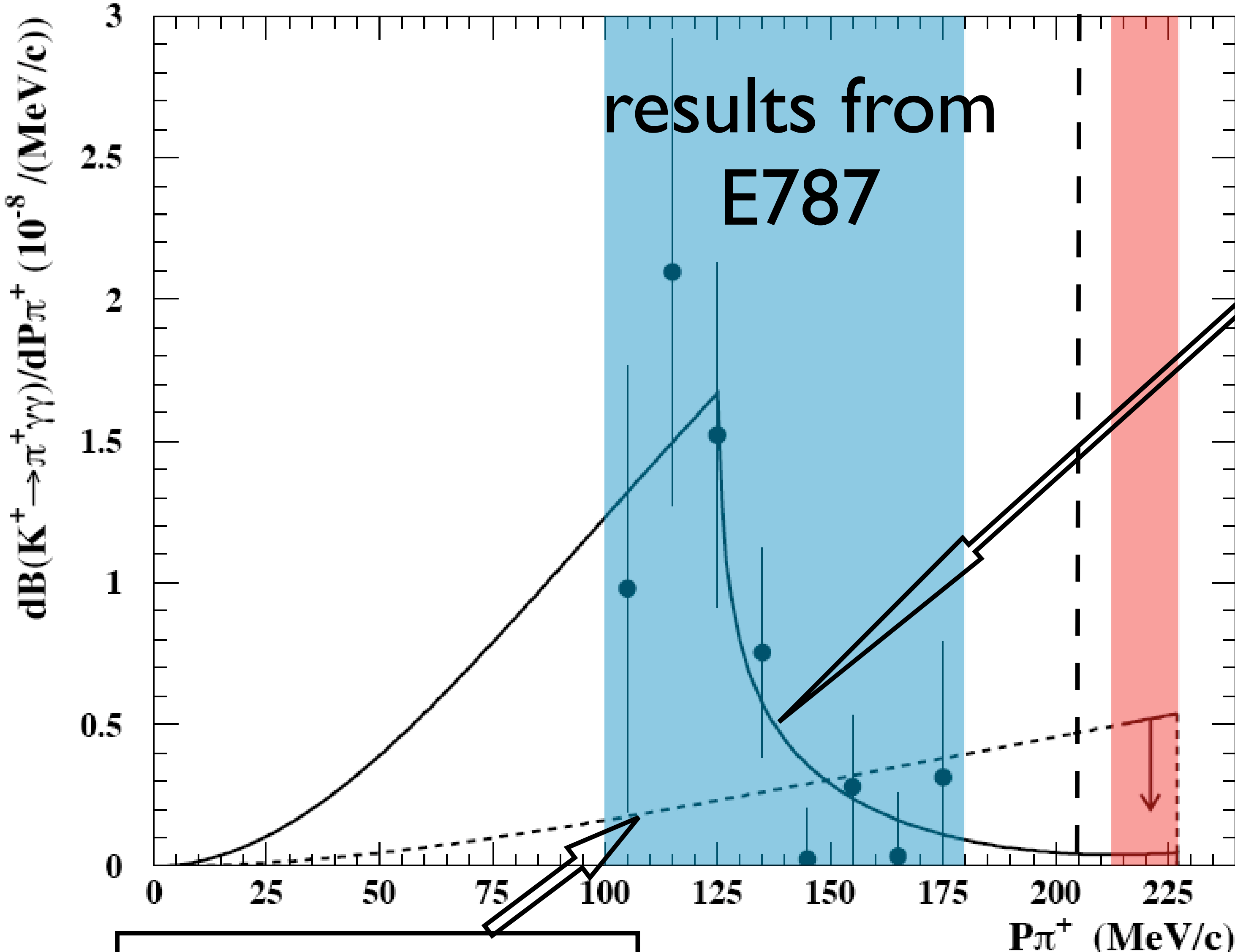
Values obtained from E787 → Values obtained from ChPT

$$\hat{c}_{No\ corr.} = 1.6 \Longrightarrow \mathcal{B}(P_{\pi^+} > 213 MeV/c) = 4.9 \times 10^{-10}$$

$$\hat{c}_{unitarity\ corr.} = 1.8 \Longrightarrow \mathcal{B}(P_{\pi^+} > 213 MeV/c) = 6.1 \times 10^{-9}$$

Order of Magnitude Different!

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



solid = Chiral Perturbation Theory (ChPT) best fit with Unitary Corrections (UC) : $\hat{C}$ = 1.8±0.6

dashed = phase-space

E787 results:

31 evts, bkg of 5.1±3.3 evts

P=(110,180)

no events observed P>215

E787 results:

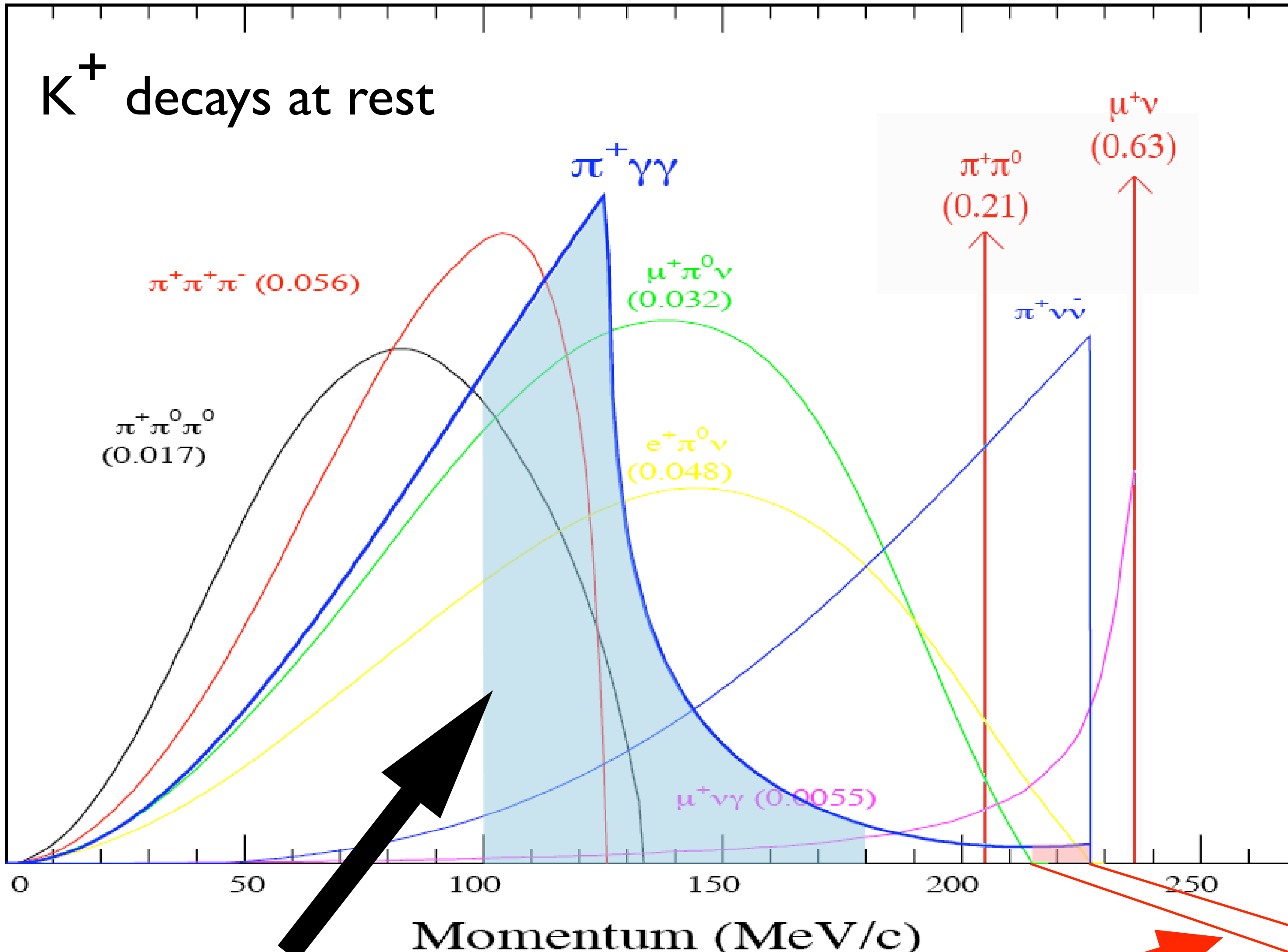
$$BR(K^+ \to \pi^+\gamma\gamma, P_{\pi+} = (110,180)\ MeV/c) = (6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$$

$$BR(K^+ \to \pi^+\gamma\gamma, P_{\pi+} > 215\ MeV/c) < 6.1 \times 10^{-8}$$

P. Kitching *et al.*, Phys. Rev. Lett. **79**, 4079 (1997).

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

Backgrounds

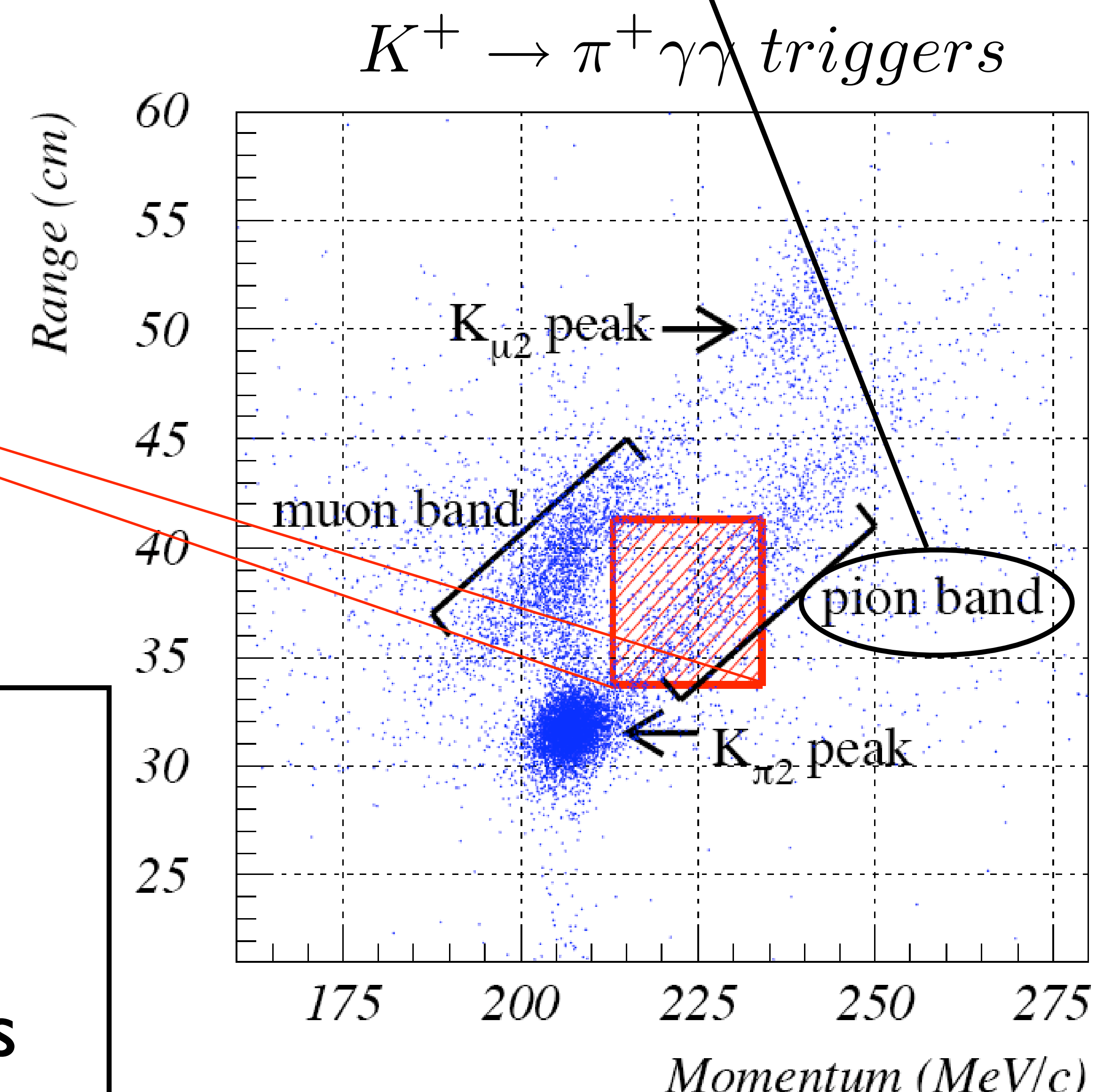


E787 Signal Region

E949 Signal Region

From beam π^+ &

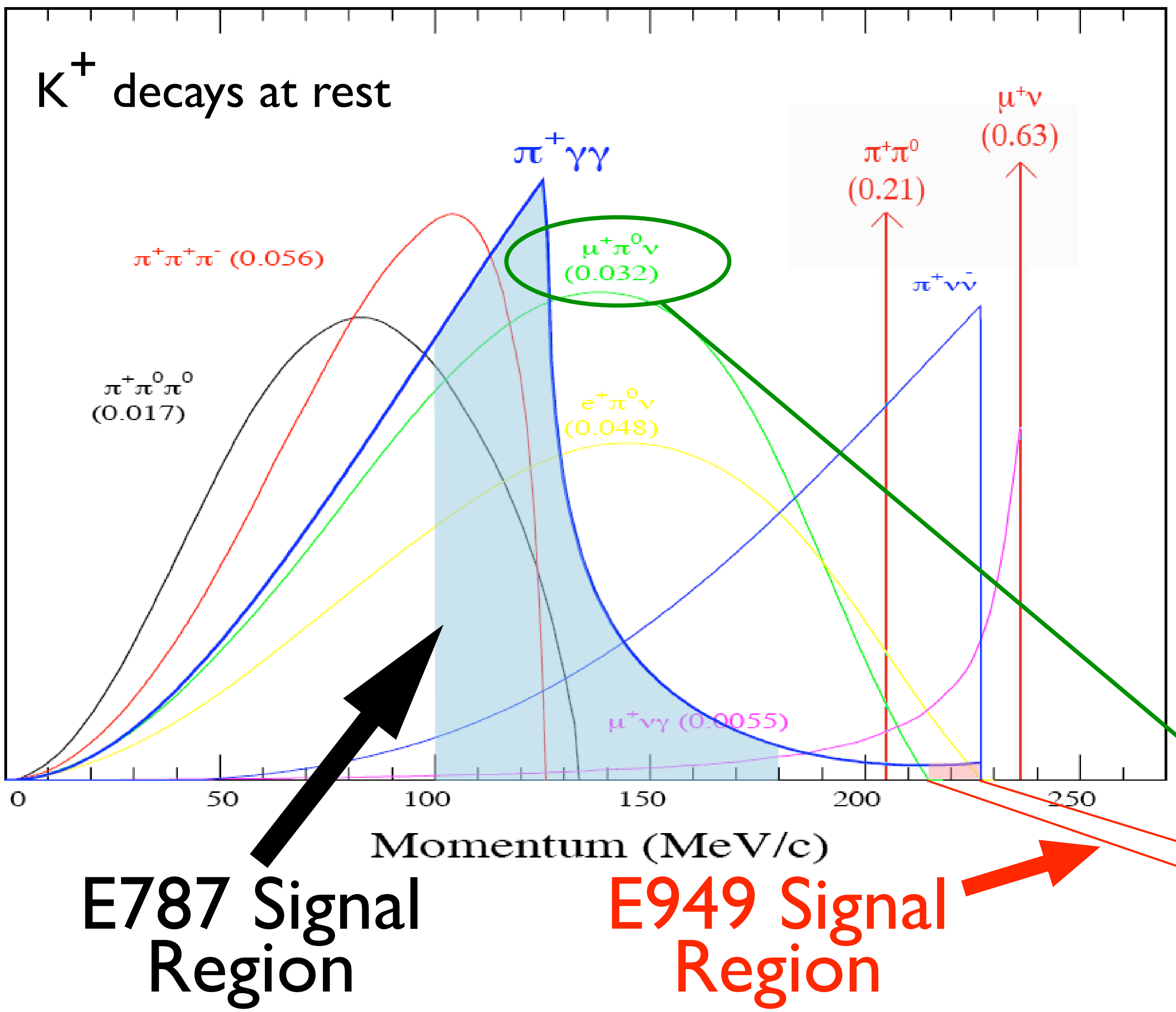
K^+ decay in flight

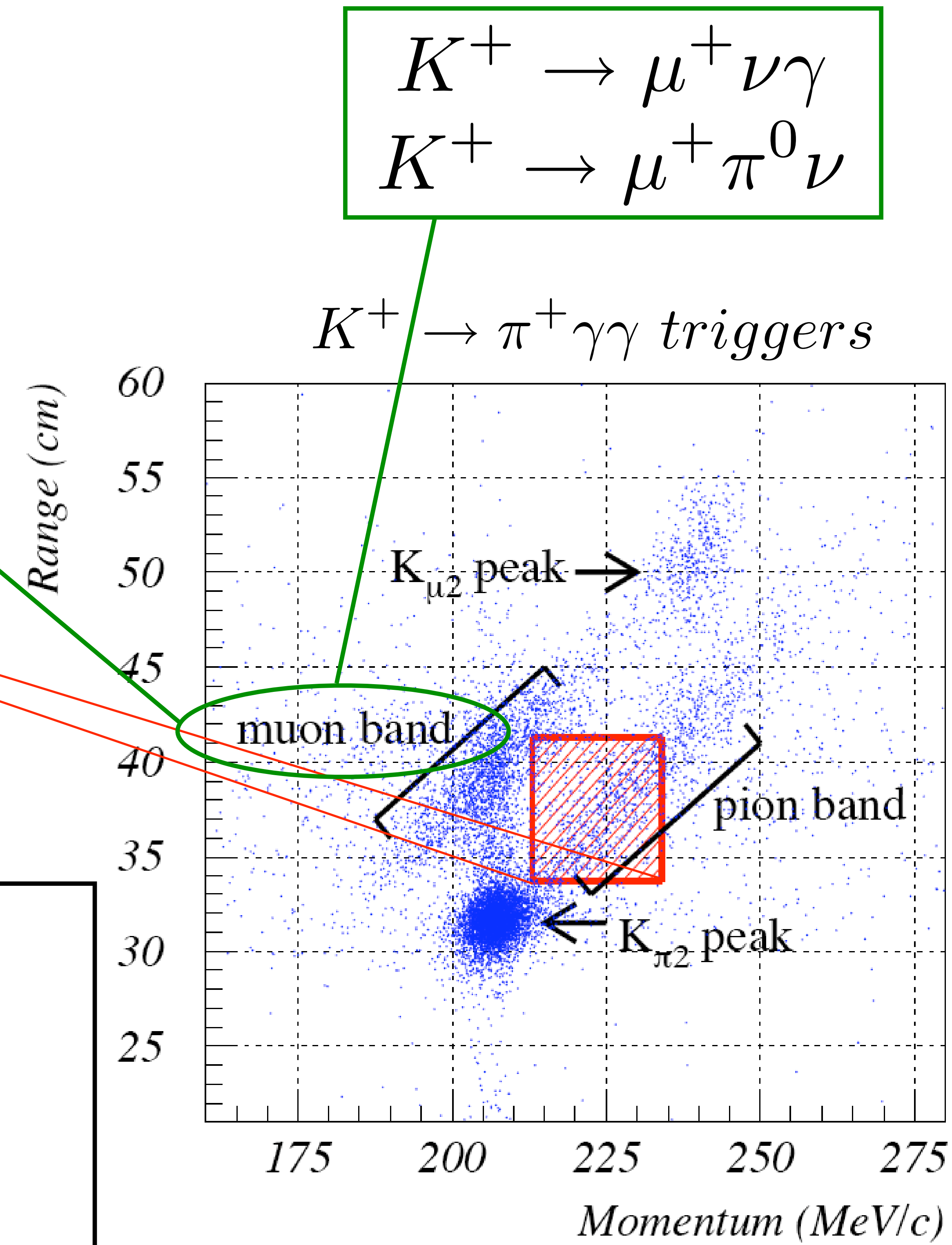


- Suppress with good segmentation & timing in K tracking system
- Fakes K decay at rest
- Suppressed with redundant timing cuts

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

Backgrounds

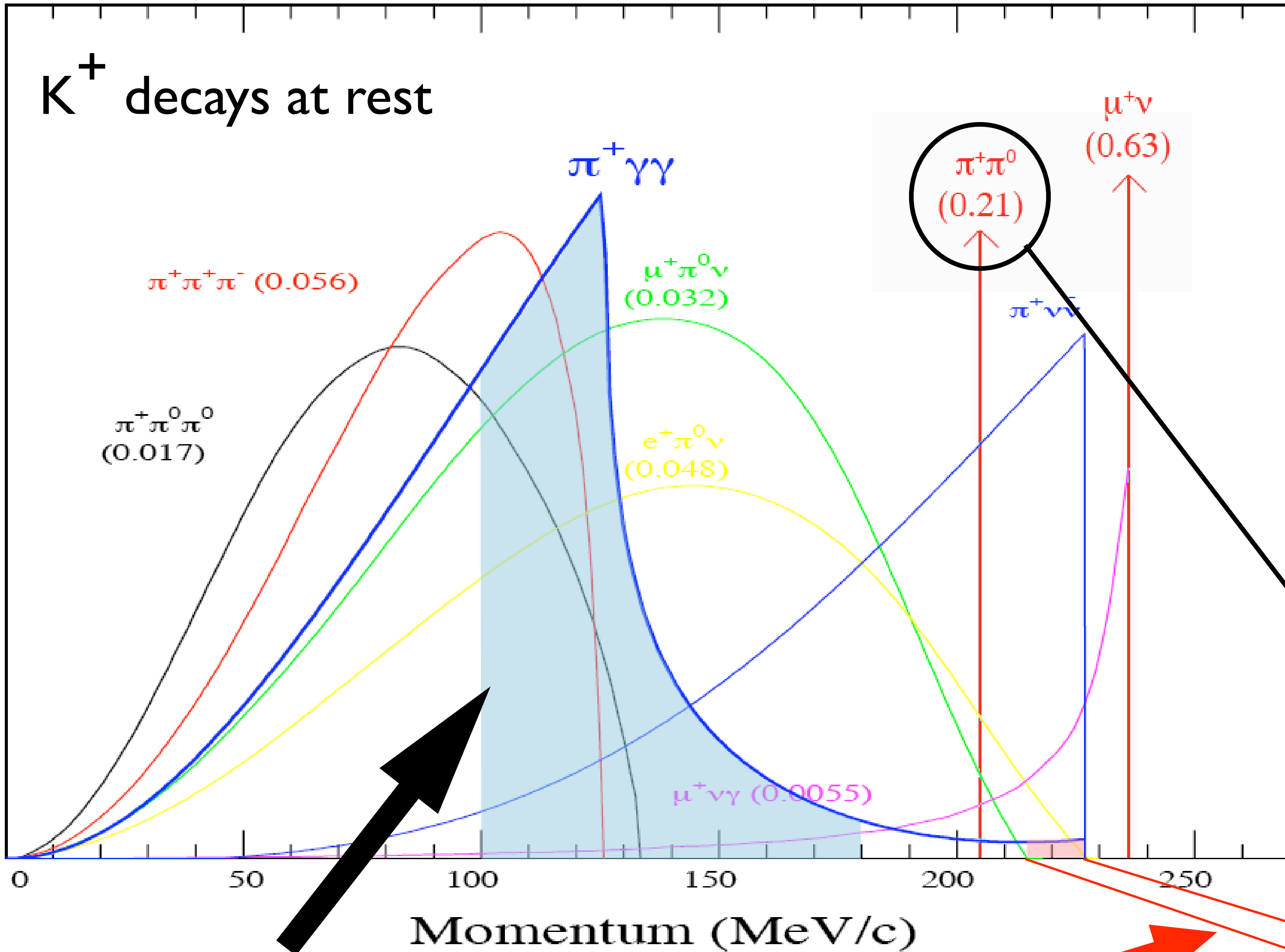




- μ kinematics mismeasured
- $\pi^+ \to \mu^+ \to e^+$ decay sequence fooled

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

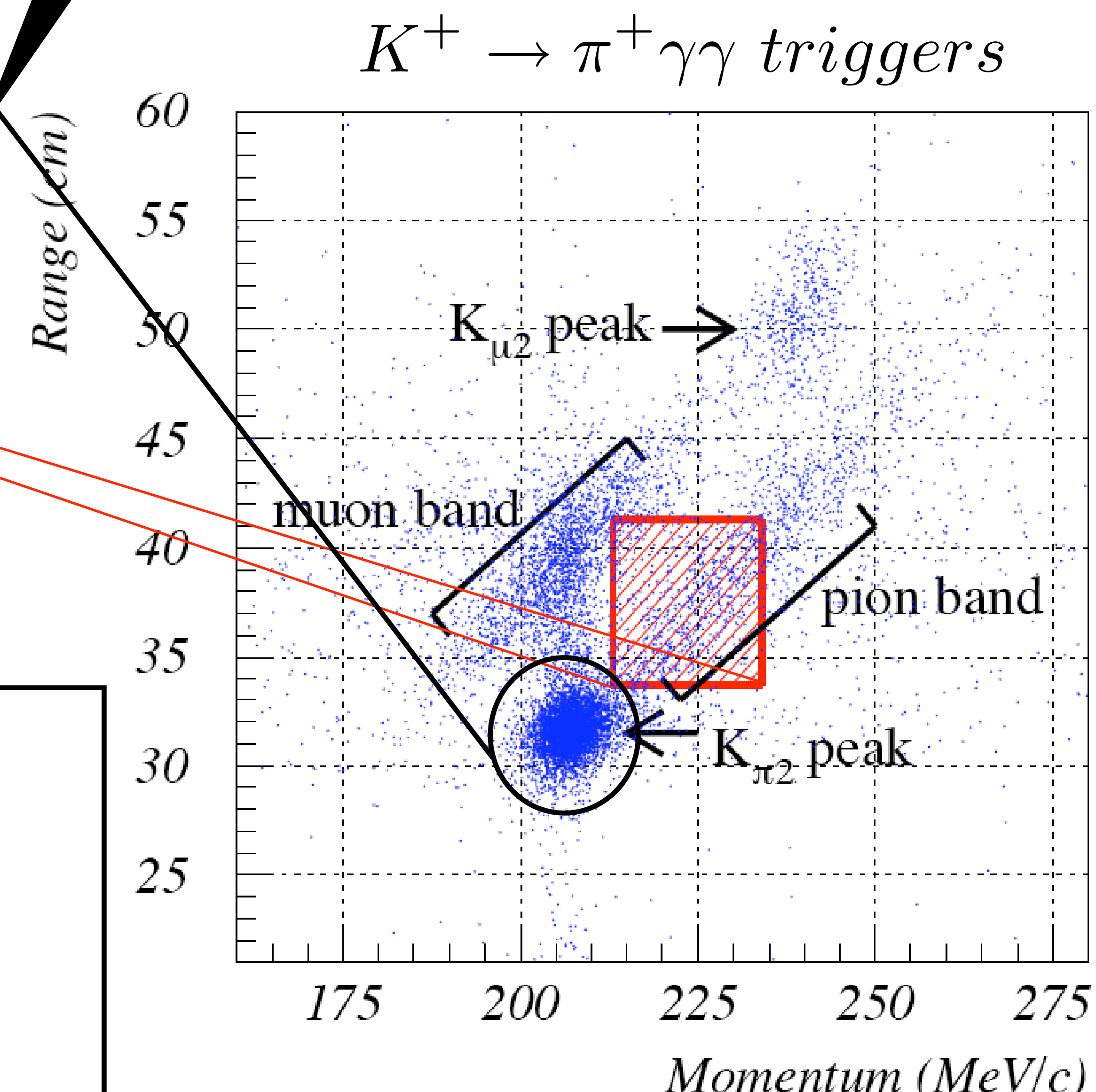
Backgrounds



Background from $K^+ \to \pi^+\pi^0$

E787 Signal Region

E949 Signal Region



- π^+ kinematics mismeasured
- Photon energies/angles mismeasured
- Photon overlaps charged track

Estimated Background

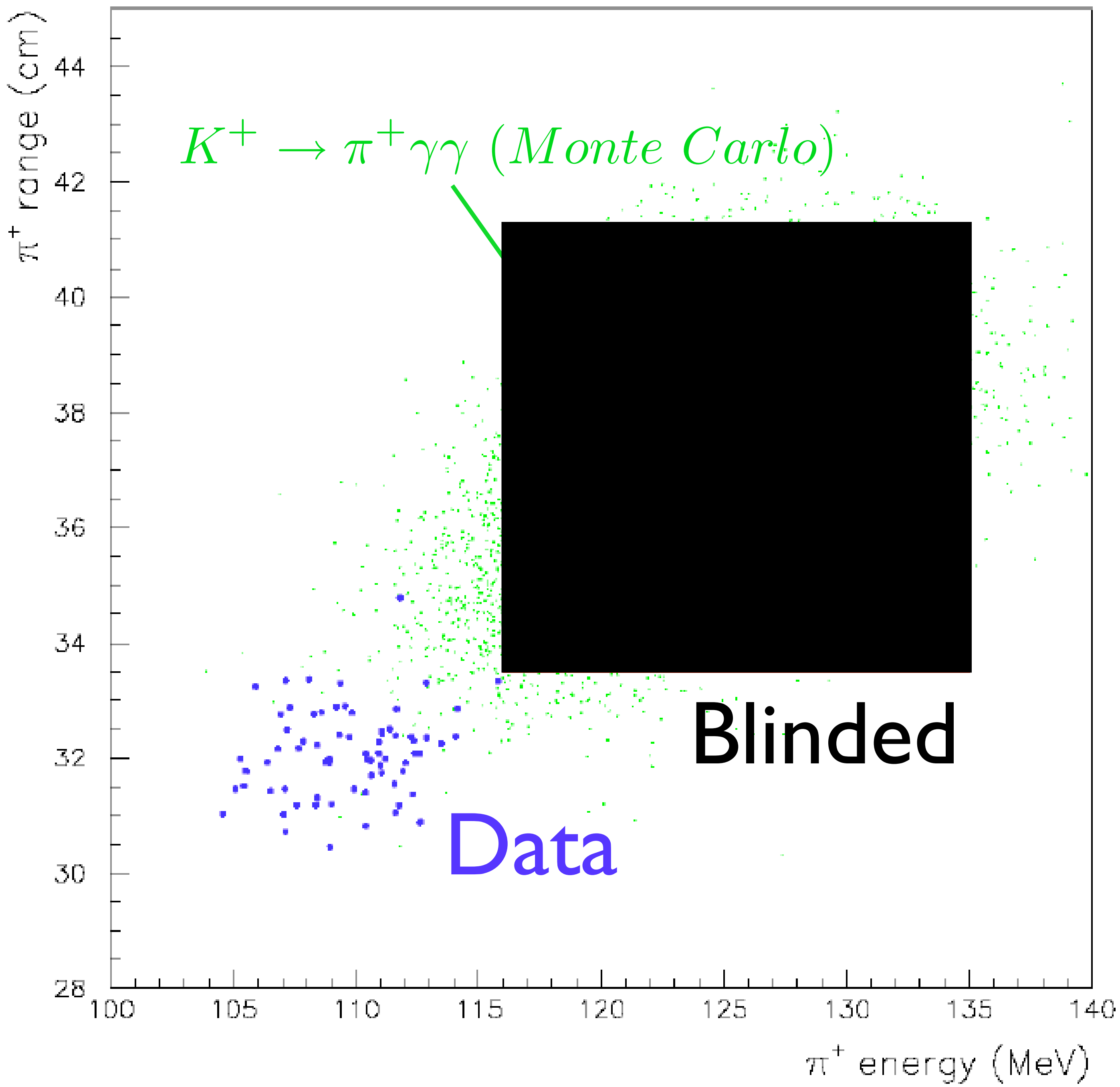
Process	number of events
$K^+ \to \pi^+\pi^0$	0.017 ± 0.006
$Overlapping\ \gamma$	0.065 ± 0.065
Muon	0.090 ± 0.020
Single Beam	0.025 ± 0.014
Double Beam	$< 0.006\ (90\%\ C.L.)$
Total	0.197 ± 0.070

Results

Background	w/UC ĉ=1.8	w/o UC ĉ=1.6
Total acceptance	$(2.99\pm0.07) \times 10^{-4}$	$(1.10\pm0.04) \times 10^{-4}$
# of stopped K^+	8.97×10^{11}	
Single Event Sensitivity	$(3.72\pm0.14) \times 10^{-9}$	$(10.1\pm0.5) \times 10^{-9}$
BR ($P_{\pi^+} > 213$)	6.10×10^{-9}	0.49×10^{-9}
Expected	1.6 events	0.05 events

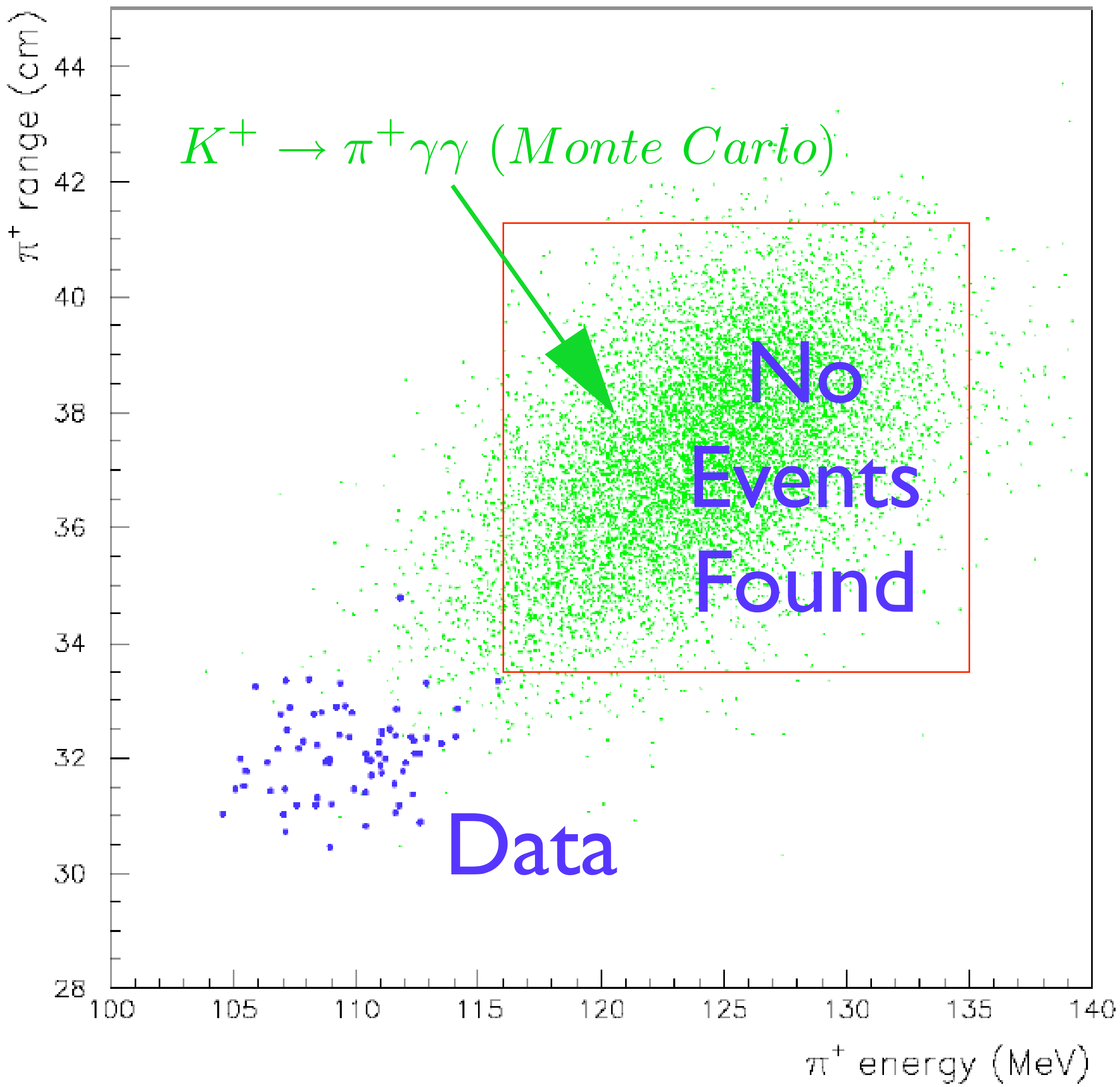
Results

E949 2002 data



Results

E949 2002 data



ChPT w/ unitarity corrections (ĉ=1.8)

$BR(K^+ \to \pi^+\gamma\gamma) < 8.3 \times 10^{-9}$ (90% CL)

$P_{\pi^+} > 213\ MeV/c$

ChPT w/o unitarity corrections (ĉ=1.6)

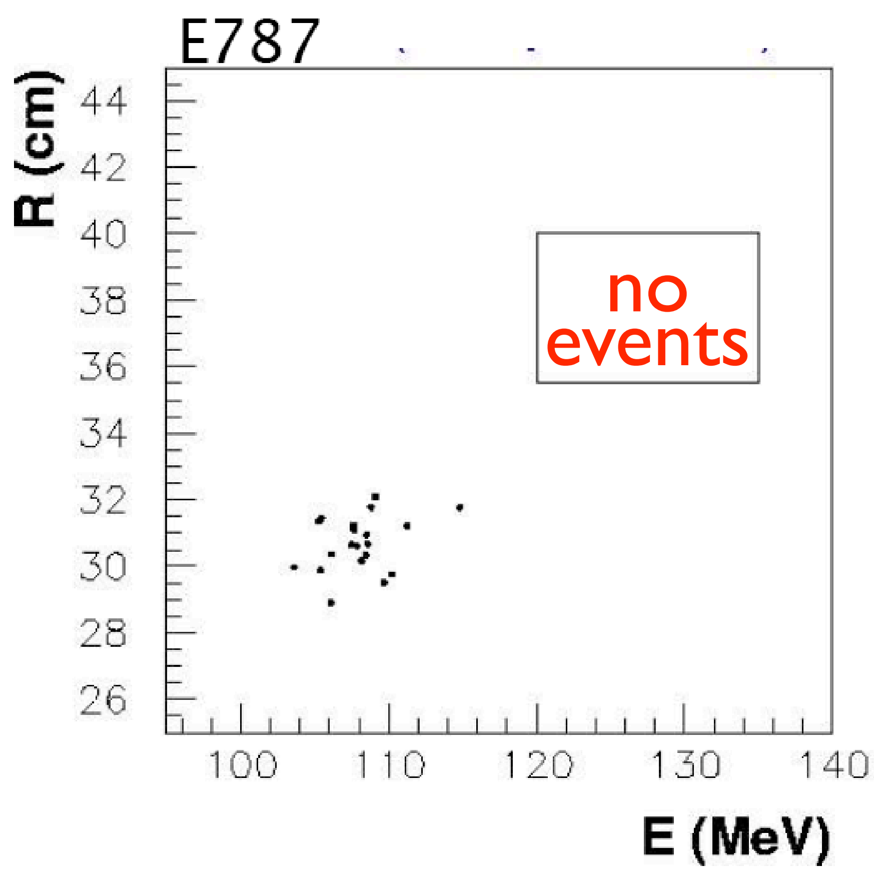
$BR(K^+ \to \pi^+\gamma\gamma) < 2.3 \times 10^{-8}$ (90% CL)

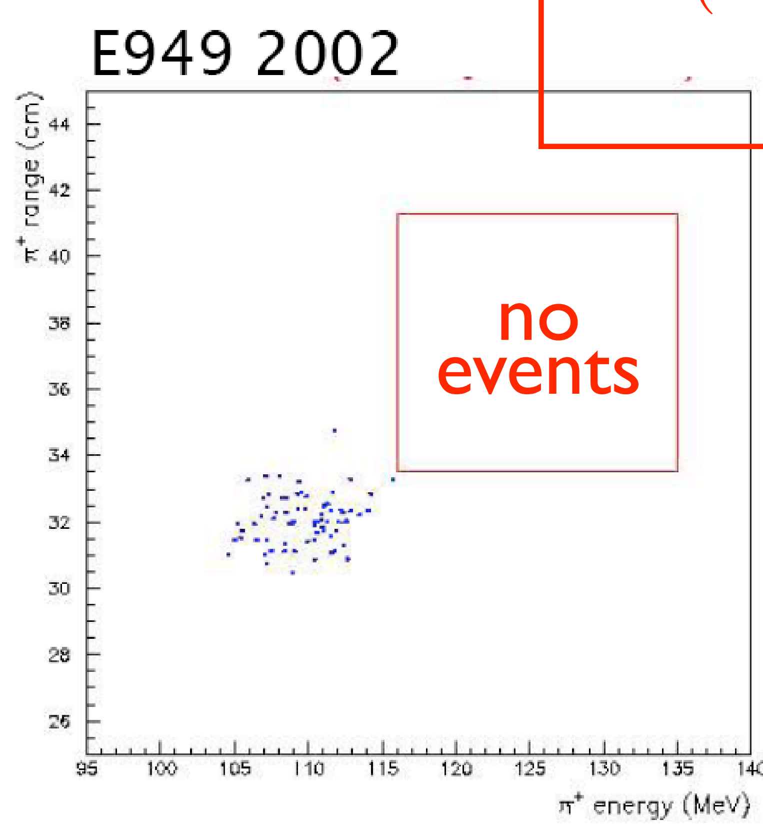
Insufficient statistics to discriminate validity of unitarity corrections.

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

- 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 modes such as non-commutative extension of SM.

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





~160X improvement over E787

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

- See User's Meeting Poster by Kentaro Mizouchi for further information.
- Forbidden by angular momentum conservation if neutrinos are massless.
- $BR(\pi^0 \rightarrow \nu\overline{\nu}) < 5 \times 10^{-10}\ for\ m(\nu_\tau) < 18.2\ MeV/c^2$ (Dirac-ν)
  $BR(\pi^0 \rightarrow \nu\overline{\nu}) < 1.1 \times 10^{-9}\ for\ m(\nu_\tau) < 18.2\ MeV/c^2$ (Majorana-ν)
- Experimental limit set by E787:
  $BR(\pi^0 \rightarrow \nu\overline{\nu}) < 8.3 \times 10^{-7}\ (90\%\ CL)$
- Method: copious supply of π^0 from $K^+ \rightarrow \pi^+\pi^0$ cleanly tagged by monochromatic π^+. Look for $K^+ \rightarrow \pi^+$ with kinematics consistent with $K_{\pi 2}$
- Trigger: same as $K^+ \rightarrow \pi^+\nu\nu$. Select $K_{\pi 2}$ & Apply the tightest photon veto.
- Photon Veto: Tune on 1/3 of the data. Use 2/3 of the data for the $\pi^0 \rightarrow \nu\nu$ search.
- Note: $\pi^0 \rightarrow \nu\nu$ search is sensitive to $\pi^0 \rightarrow XX$ where X is a weakling-interacting neutral particle.

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

$\pi^0 \rightarrow \nu\overline{\nu}$ *result*

- Observe 99 $\pi^0 \rightarrow \nu\nu$ candidate events from $K_{\pi 2}$ = 3 x 10^9 events
- Failure to detect photons from π^0 are due to sampling fluctuations in electromagnetic shower of low energy photons ~20 MeV & for photons >20 MeV photonuclear interactions with undetected products.
- Photon detection inefficiency in E949 not fully understood.
- Treat the 99 events as candidates
  - We are unable to subtract these events (discussed in poster)
- $BR(\pi^0 \rightarrow \nu\overline{\nu}) < 2.7 \times 10^{-7}$ $(90\%\ CL)$
- 3X improvement over previous results.

$Update\ on\ K^+ \rightarrow \pi^+ \nu\bar{\nu}\ for\ P_{\pi^+} = [140, 199]$

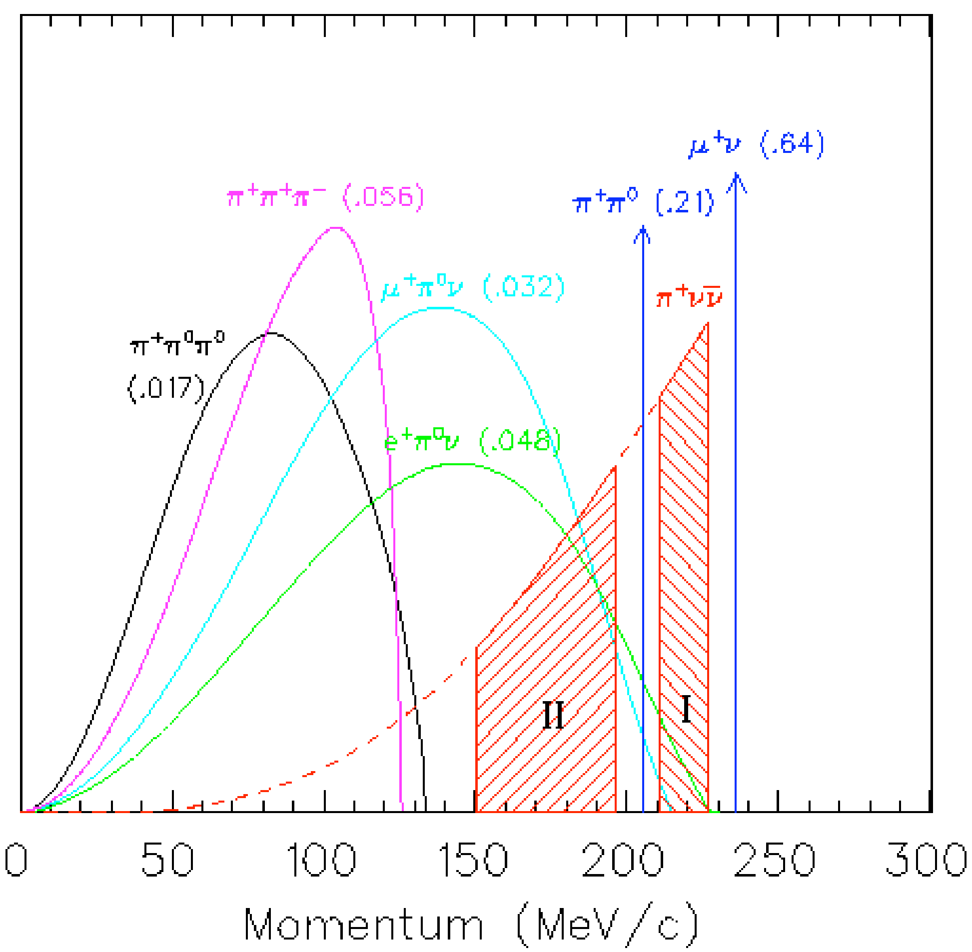
E949 detector optimized for this decay

Goal is to obtain

Signal/Background = 1/1

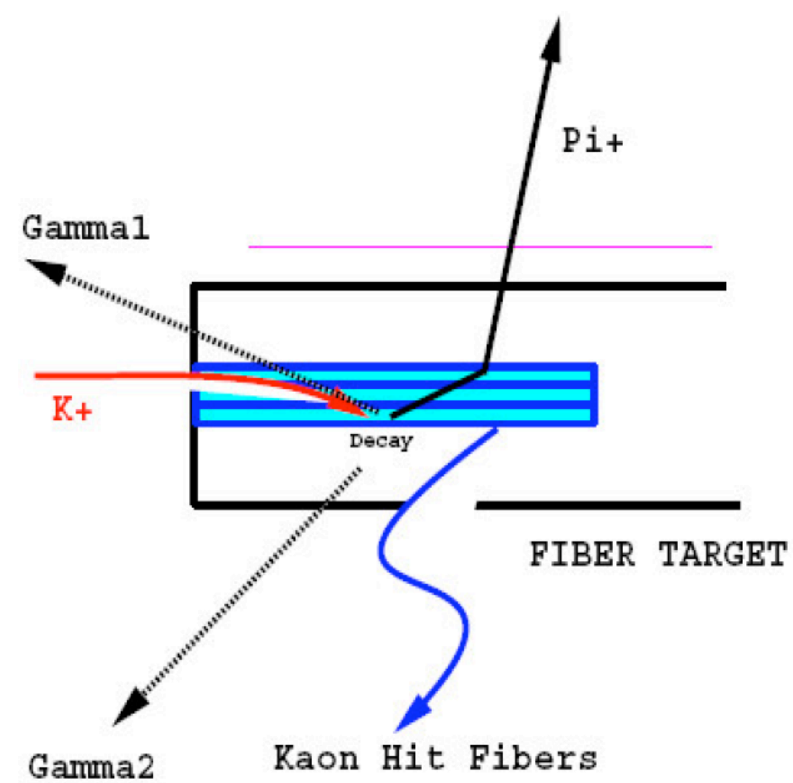
E787 S/B ~ 1/10

not to scale



More phase space than PNN1

$K_{\pi 2}$-scatter Background > 80% of total background in E787.



$Update\ on\ K^+ \rightarrow \pi^+\nu\overline{\nu}\ for\ P_{\pi^+} = [140, 199]$

- Current beam background estimate inline with E787.
- Photon Veto: New Tools
  - Barrel Veto Liner
    - new to E949
  - Barrel Veto Liner with Transient Digitizers
    - helps with blindness
    - new to E949-PNN2
  - Beam PV addition of Active Degrader
    - helps w/ target scatters
    - new to E949
- A powerful target scattering cut with has a low acceptance.
  - E787 Acceptance ~ 30%
  - Work to improve acceptance.

Conclusions

- E949, although optimized for $K^+ \rightarrow \pi^+ \nu\nu$, is sensitive to a number of other rare decay modes, particularly those involving photons.
- From E787 (1998 data) preliminary
- $BR_{DE}(K^+ \rightarrow \pi^+\pi^0\gamma, T_{\pi^+} = (55, 90)MeV) = (3.5 \pm 0.6 \,^{+0.3}_{-0.4}) \times 10^{-6}$
- From E949 (2002 data) Final
- $BR(K^+ \rightarrow \pi^+\gamma\gamma) < 8.3 \times 10^{-9}$ $(90\%\ CL)$ $P_{\pi^+} > 213\ MeV/c$
  $BR(K^+ \rightarrow \pi^+\gamma) < 2.3 \times 10^{-9}\,(90\%\ CL)$
- $BR(\pi^0 \rightarrow \nu\overline{\nu}) < 2.7 \times 10^{-7}$ $(90\%\ CL)$
- These are the most stringent limits available for these decay modes
- E949-PNN2 complete in < 1 year.

References

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

T. Tsumemi, 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
A.V. Artamonov, et al.,Phys. Lett. B **623** (2005) 192-199.

$\pi^0 \rightarrow \nu\nu$

K. Mizouchi, Kyoto Univ. thesis
A.V. Artamonov, et al.,Phys. Rev. D **72** 091102(R) (2005) .

extra slides

E787 Collaboration

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

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%

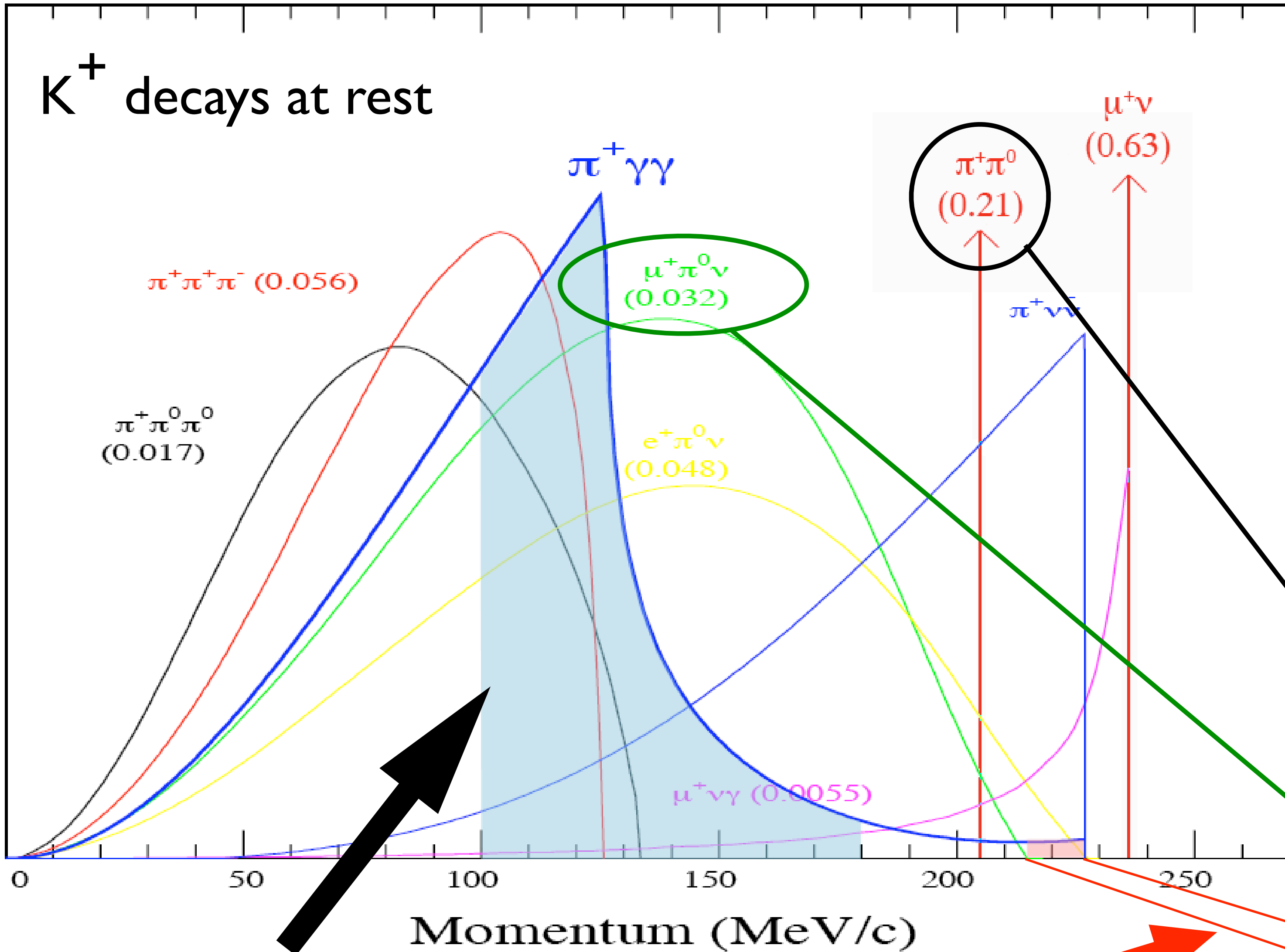
Background and Acceptance

$K^+ \rightarrow \pi^+ \nu\nu$ Technique

- Signal box blinded.
- Background estimated using "dual cut" technique.
- 1/3 data is used in setting cuts.
- Apply fixed cut to remaining 2/3 for unbiased estimate.
- Background estimates are checked by comparing prediction to observation near signal region.
- Acceptance measured from data if possible. MC used for trigger, fiducial cuts, phase space, γ reconstruction & PV cuts that depend on kinematics.

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

Backgrounds



E787 Signal Region

E949 Signal Region

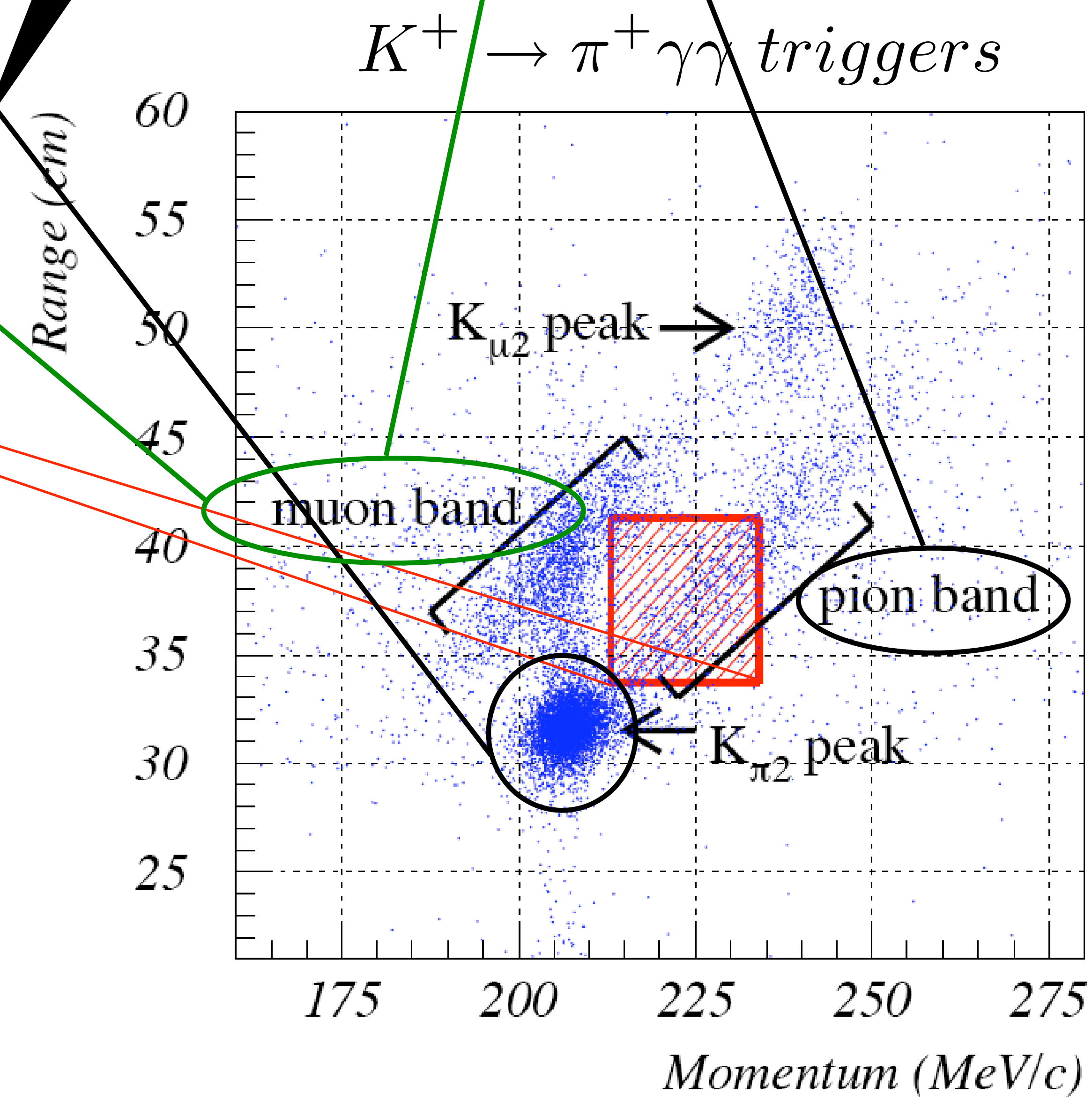
Background from $K^+ \to \pi^+\pi^0$

From beam π^+ & K$^+$ decay in flight

$K^+ \to \mu^+\nu\gamma$

$K^+ \to \mu^+\pi^0\nu$

$K^+ \to \pi^+\gamma\gamma$ *triggers*



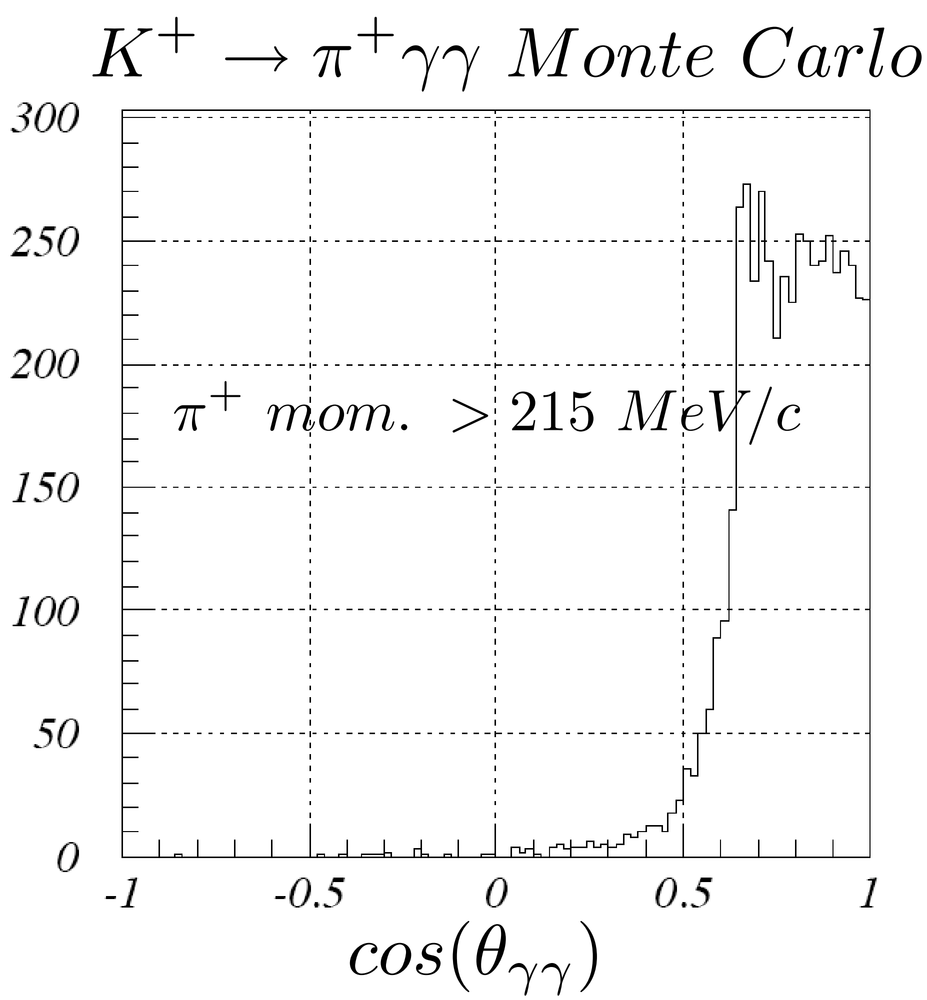
$$K^+ \to \pi^+\pi^0; \pi^0 \to \gamma\gamma$$

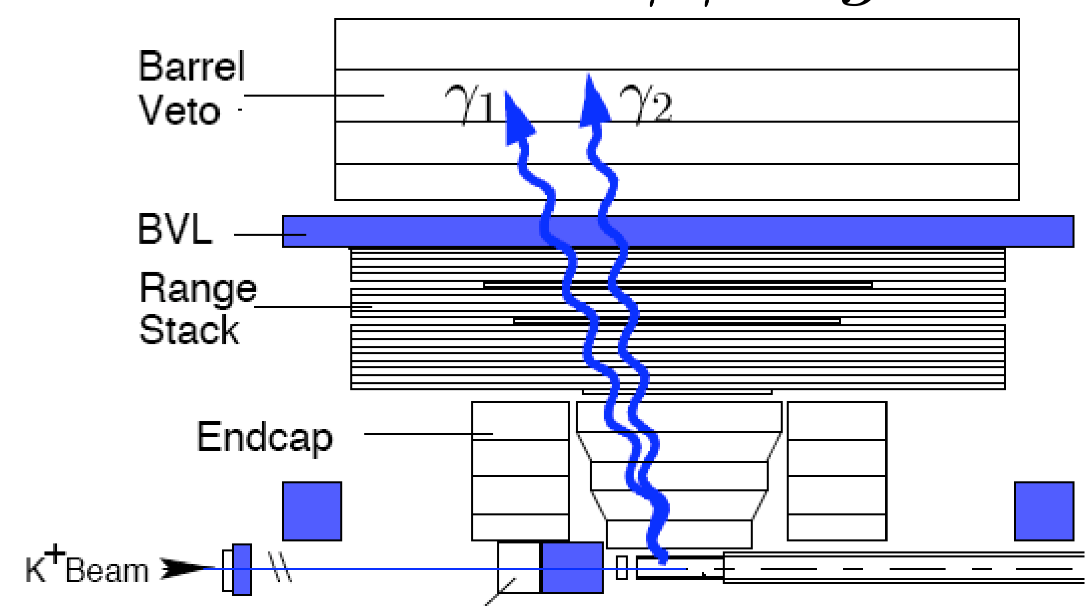
same final state

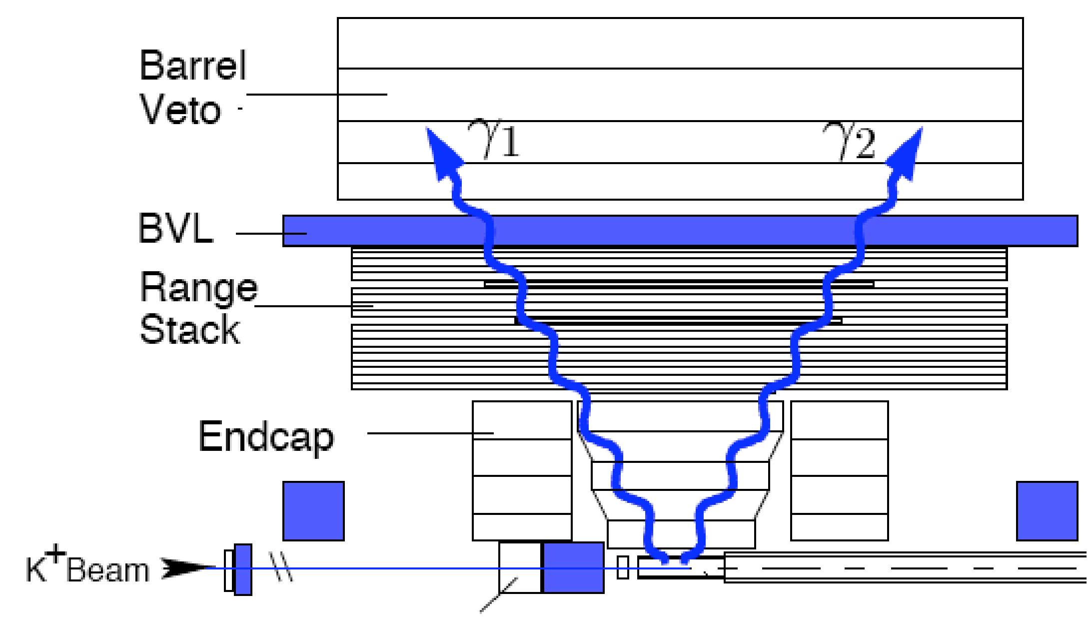
$K^+ \to \pi^+\pi^0$ *Background*

Suppress backgrounds

- *Use* π^+ *kinematics*
- *Opening angle cut on* γ*s*



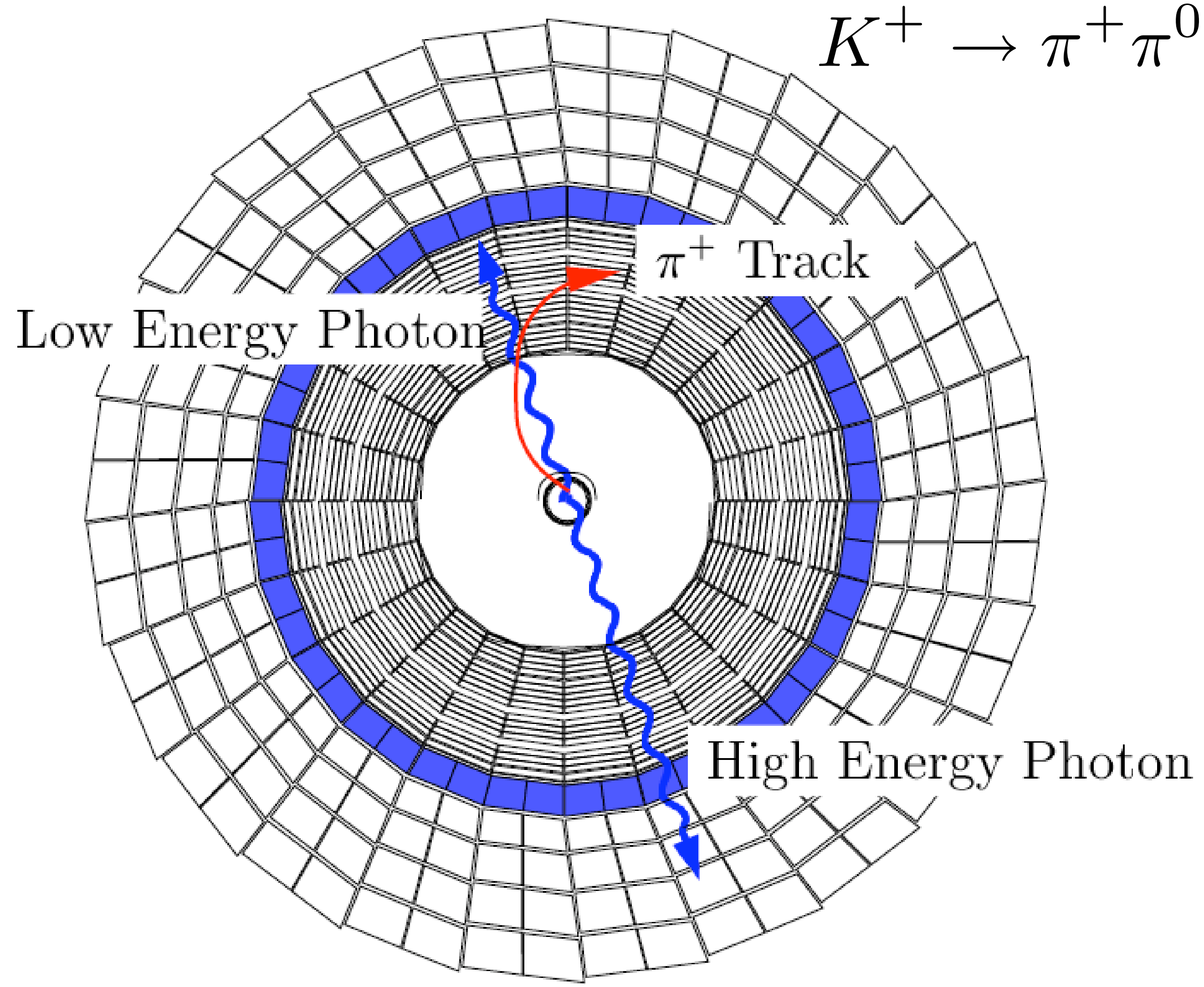




$K^+ \to \pi^+\gamma\gamma$

Overlapping γ Background

- Cut on overlapping γ by observing larger than expected energy.



Results

Background	w/UC ĉ=1.8	w/o UC ĉ=1.6
Total acceptance	$(2.99\pm0.07) \times 10^{-4}$	$(1.10\pm0.04) \times 10^{-4}$
N_{kaon}	1.19×10^{12}	
K^+ stopping efficiency	0.754 ± 0.124	
Single Event Sensitivity	$(3.72\pm0.14) \times 10^{-9}$	$(10.1\pm0.5) \times 10^{-9}$
BR ($P_{\pi^+} > 213$)	6.10×10^{-9}	0.49×10^{-9}
Expected	1.6 events	0.05 events

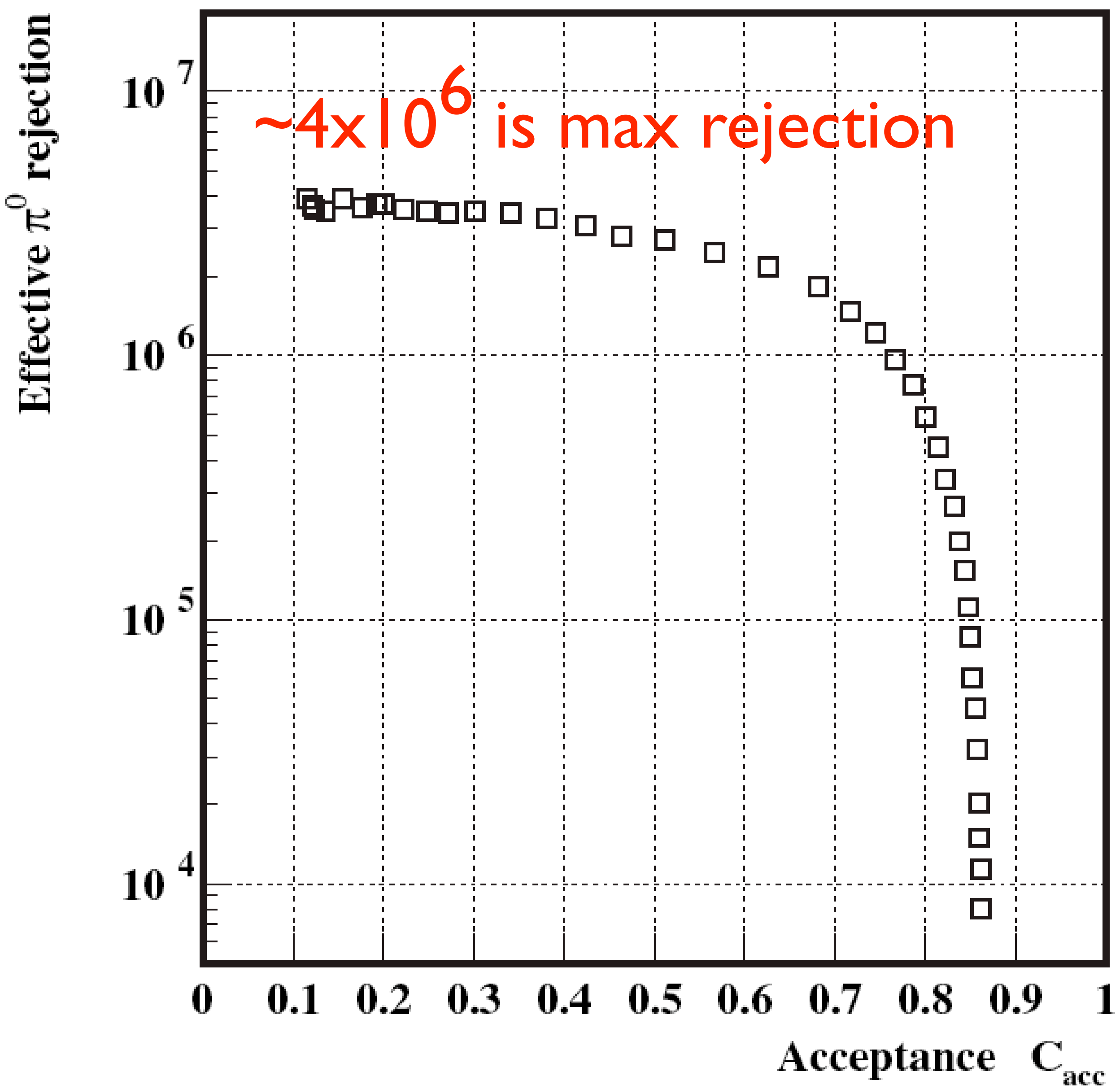
Acceptance $A^{\pi^+\gamma\gamma}_{O(p^6)} = 1.550 \pm 0.034 \times 10^{-4}$

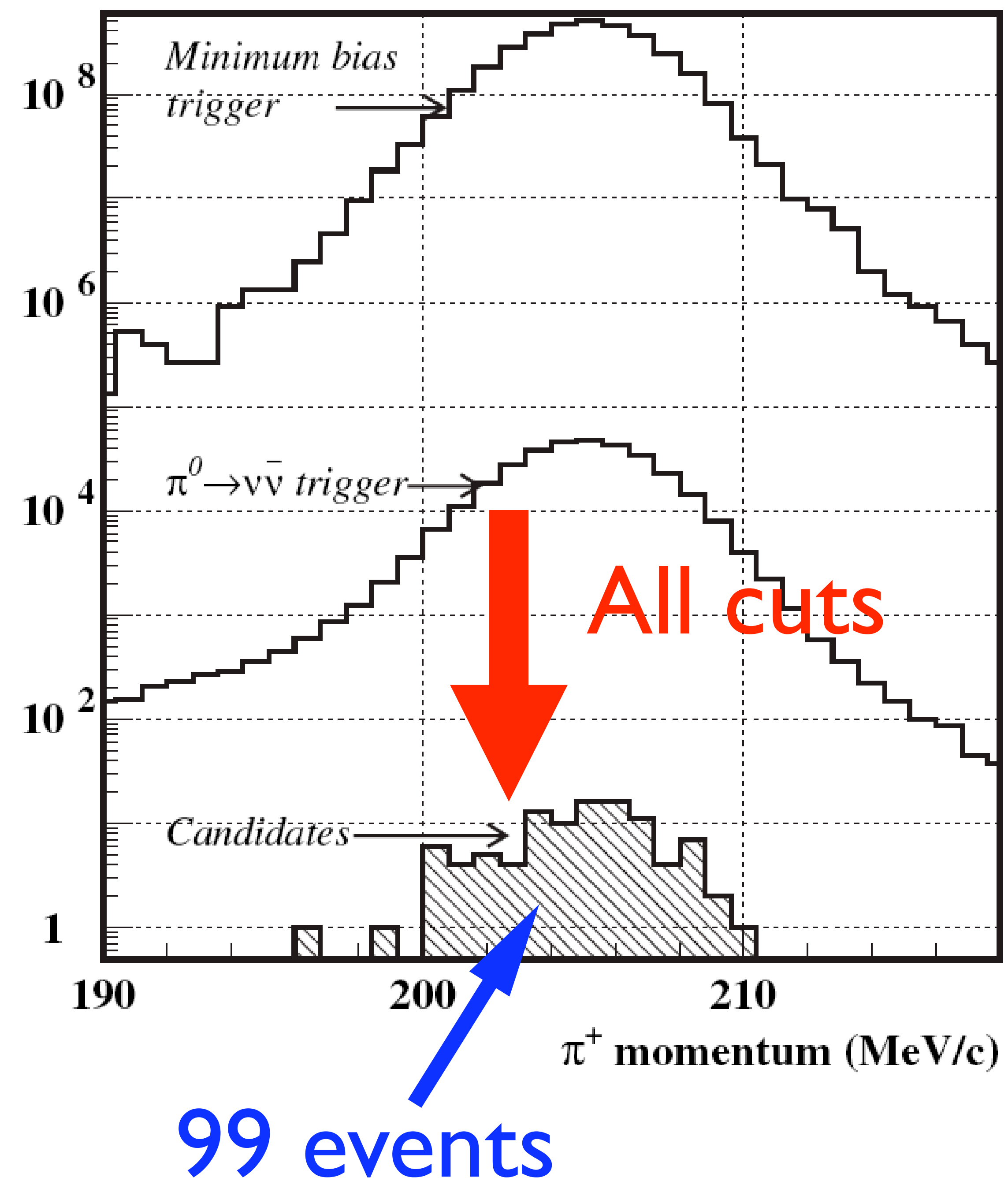
Expected Number of Events **1.6**

(assuming unitarity corrections)

π^0 rejection

Rejection x Acceptance





$K_{\pi 2}$ candidates = 3×10^9