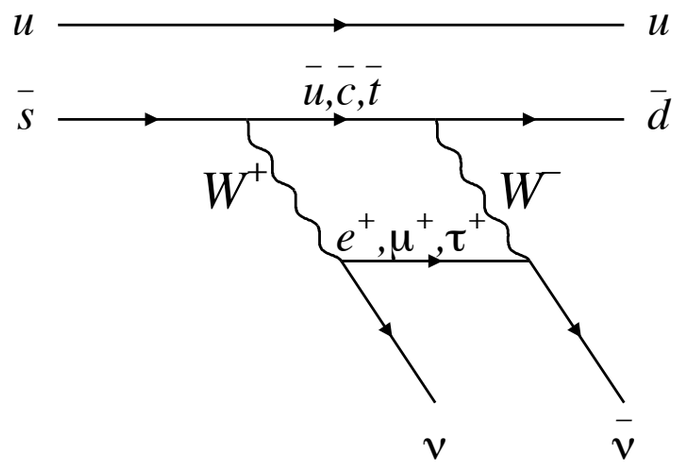
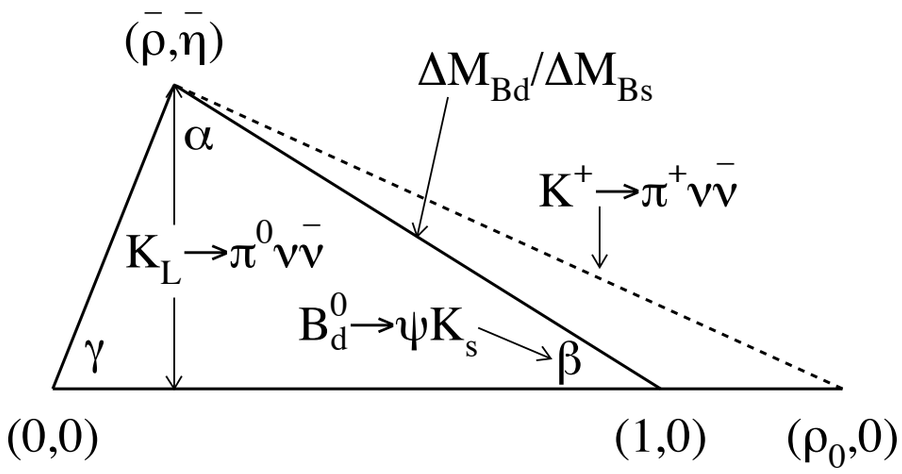
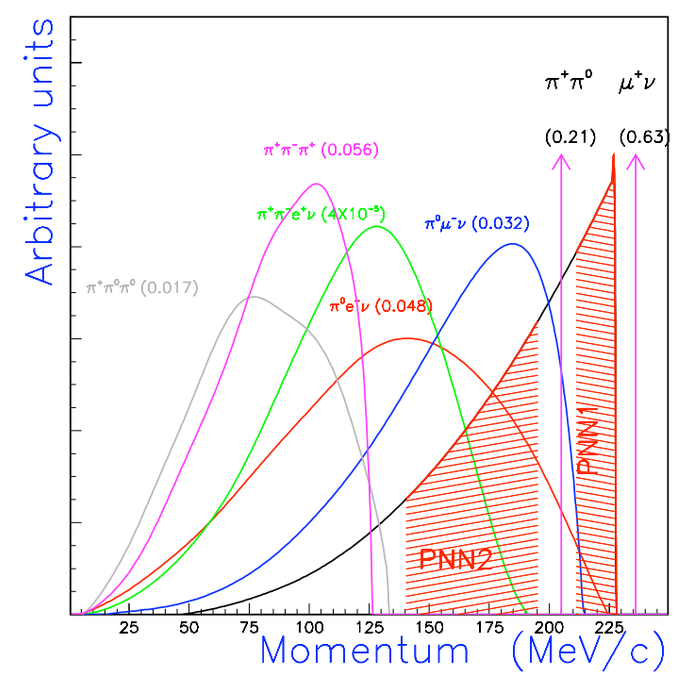
The Quest for the Rare Decay $K^+ \to \pi^+ \nu \bar{\nu}$

Benji Lewis
University of New Mexico

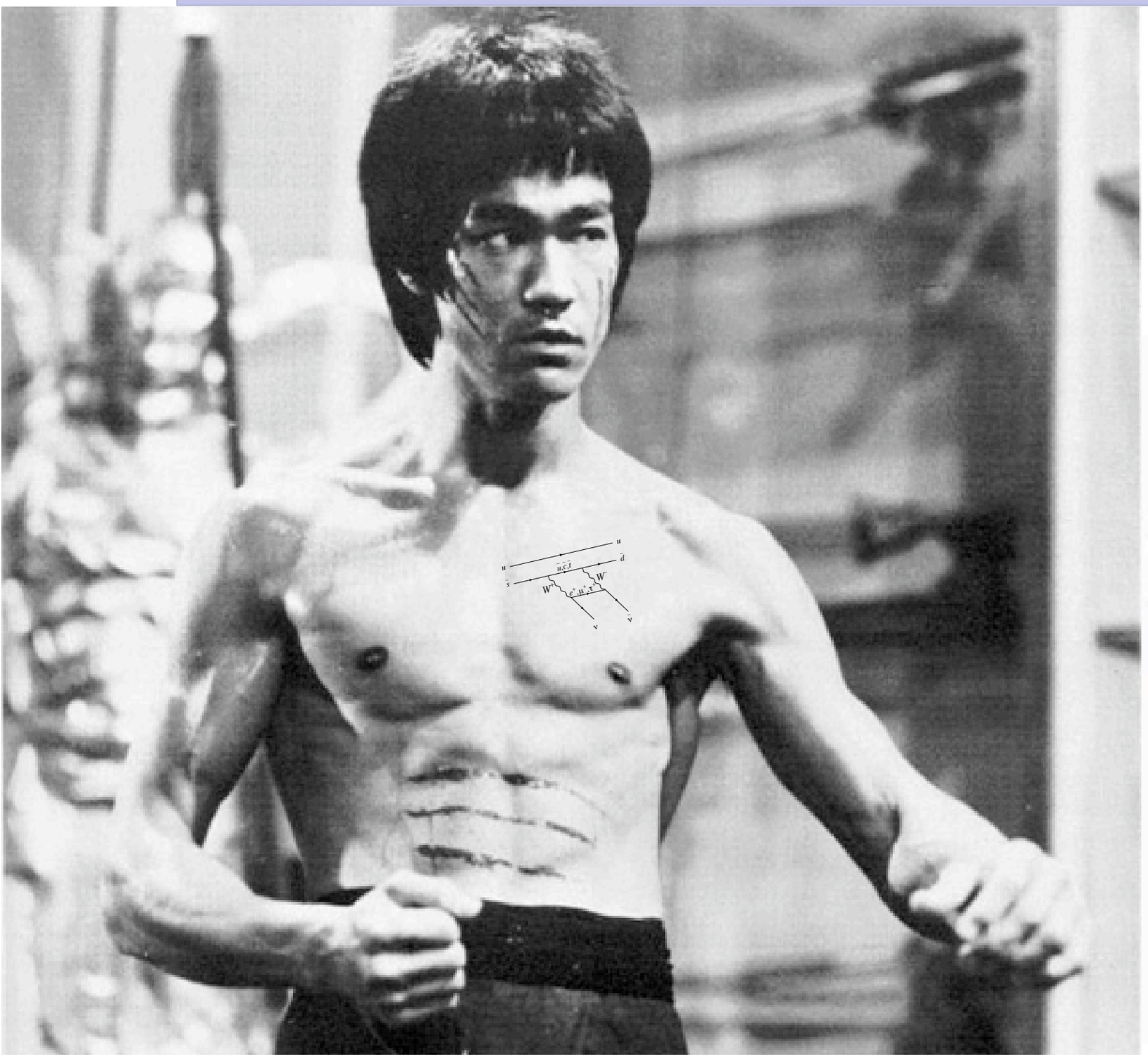






Alternate Title

E949 and the Legend of the Black Box



E949 Collaboration

117 collaborators, 17 institutes from Canada, China, Japan, Russia and the US.

A.J.S. Smith, A.J. Stevens, A.N. Khotjantsev, A.O. Bazarko, A.P. Ivashkin, A.P. Kozhevnikov, A.S. Turcot, A.V. Artamonov, A. Daviel, A. Konaka, A. Kushnirenko, A. Otomo, A. Sambamurti, B. Bassalleck, B. Bhuyan, **B. Lewis**, B. Viren, C. Ng, C. Ng, C. Witzig, D.A. Bryman, D.E. Jaffe, D.I. Patalakha, D.R. Marlow, D.V. Vavilov, D. Akerib, E.J. Ramberg, E.W. Blackmore, E. Garber, F.C. Shoemaker, G. Azuelos, G. Redlinger, I-H. Chiang, **I.-A. Christidi**, J.-M. Poutissou, J.A. Macdonald, J. Doornbus, J.R. Stone, J.S. Frank, J.S. Haggerty, J.V. Cresswell, J. Hu, **J. Ives**, J. Mildenberger, J. Roy, K.K. Li, K. Mizouchi, K. Omata, K. Shimada, L. Felawka, L.G. Landsberg, L.S. Littenberg, M. Aoki, M. Miyajima, M.A. Selen, M.LeNoble, M.M. Khabibullin, M.V. Diwan, M. Ardebili, M. Burke, M. Convery, M. Ito, M. Kobayashi, M. Kuriki, M. Nomachi, M. Rozon, M.S. Atiya, N.V. Yershov, N. Muramatsu, O.V. Mineev, P.C. Bergbusch, P.D. Meyers, P.S. Cooper, P. Kitching, P. Padley, P. Pile, R.C. Strand, R.Soluk, R. McPherson, R. Poutissou, R. Tschirhart, S.H. Kettell, S.V. Petrenko, S. Adler, S. Chen, S. Daviel, S. Kabe, S. Ng, S. Sugimoto, T.F. Kycia, T.K. Komatsubara, T. Fujiwara, T. Inagaki, T. Nakano, T. Nomura, T. Numao, T. Sasaki, T. Sato, T. Sekiguchi, T. Shimoyama, T. Shinkawa, T. Tsunemi, T. Yoshioka, V.A. Kujala, V.A. Mukhin, V.F. Obraztsov, V.V. Anisimovsky, V. Jain, W.C. Louis, W.Sands, Y. Kishi, Y. Kuno, Y. Tamagawa, Y. Yoshimura, Yi Zhao, Yu.G. Kudenko, and Zhe Wang

Budd: *You're telling me she cut through nine-hundred fourty-nine bodyguards before she got to O-Ren?*

Bill: *Nah, there weren't really nine-hundred fourty-nine of them. They just called themselves "The Crazy E949."*

Budd: *How come?*

Bill: *I don't know. I guess they thought it sounded cool.*

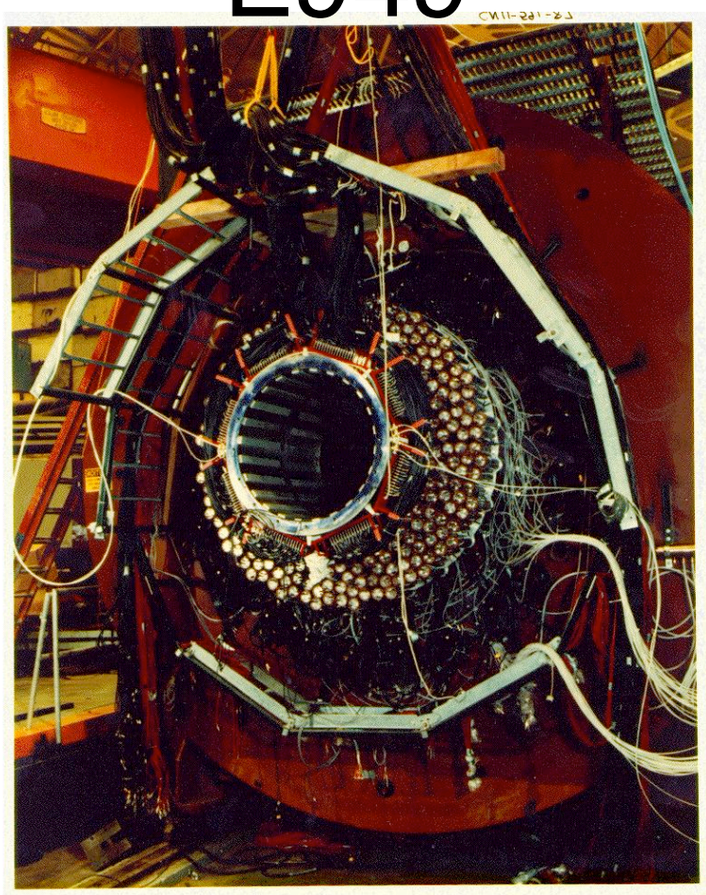
Kill Bill: Vol 2; BNL version

Matter-Antimatter Asymmetry

"I seek not to know the answers, but to understand the questions.
Caine (Kung Fu)

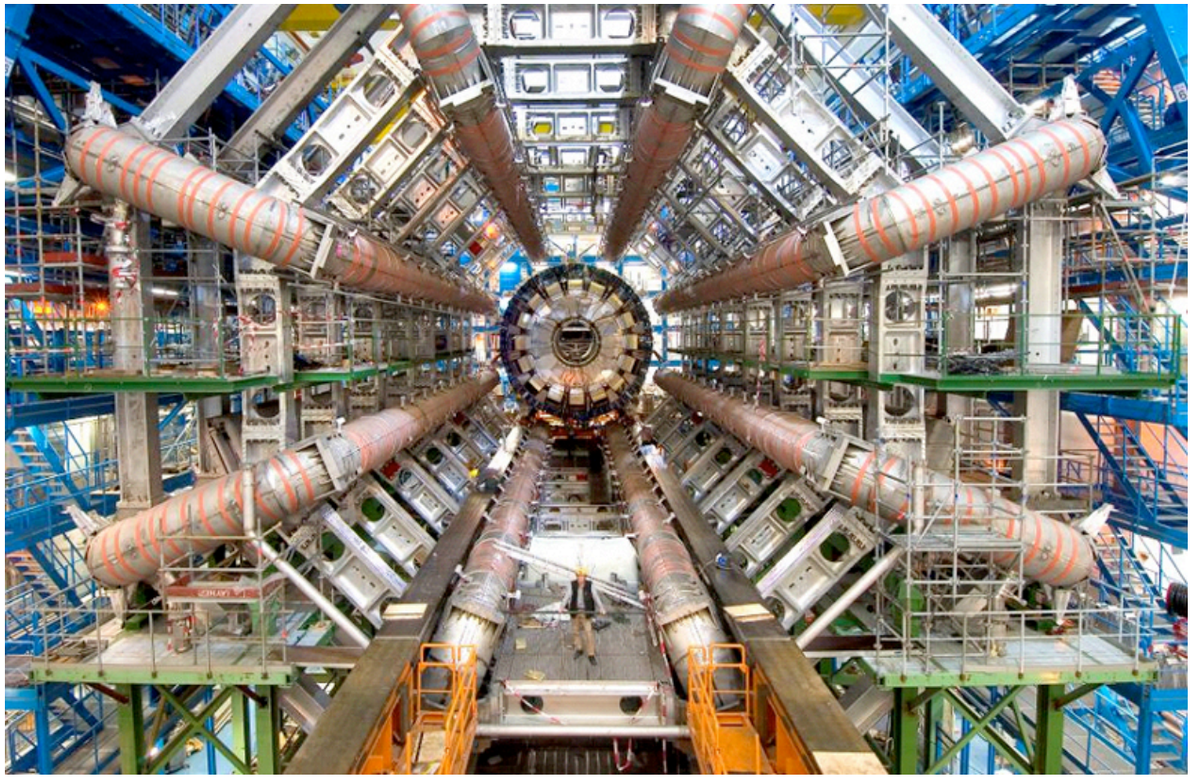
- SM predicts all *observed* CP violation phenomena.
- Predicted SM CP violation **not** sufficient to explain matter-antimatter asymmetry of the Universe.

E949



-CP Violation

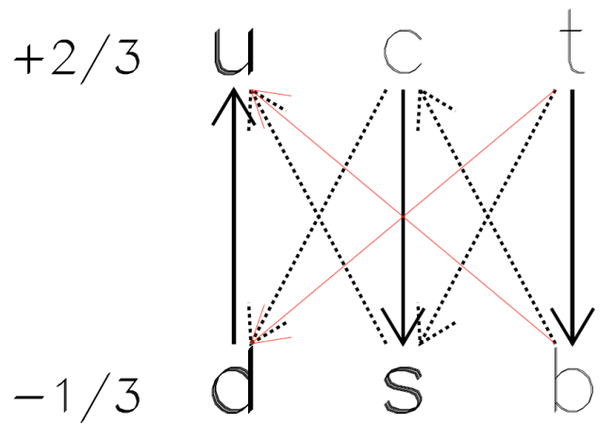
LHC



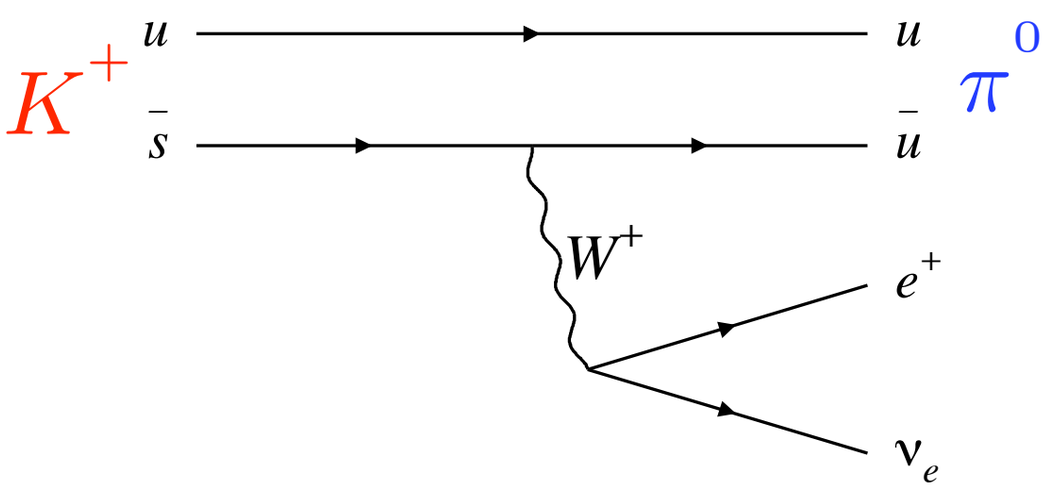
-Dark Matter/Energy

- Measurements of weak decays, such as $K^+ \to \pi^+ \nu \bar{\nu}$, may find disagreement of theory and experiment.

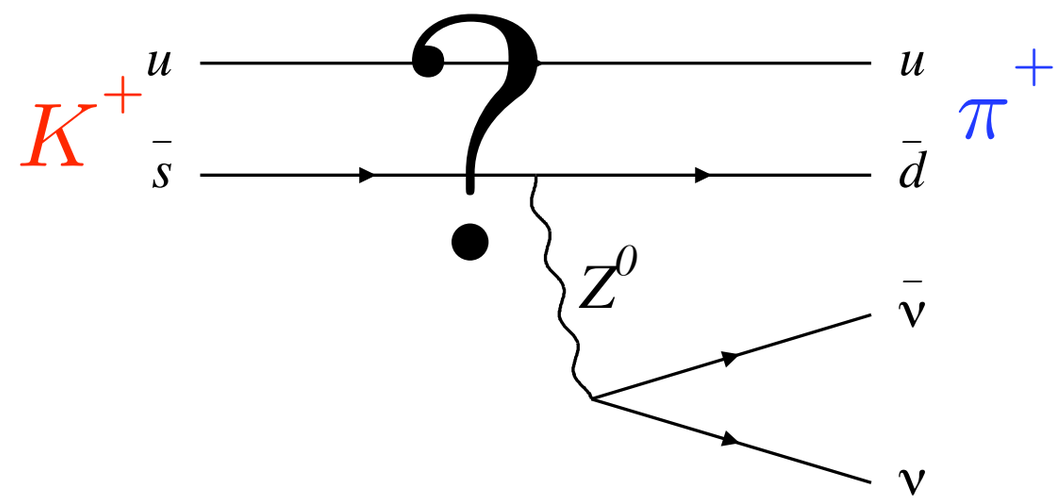
$K^+ \to \pi^+ \nu\bar{\nu}$ Theory



- Quarks decay to lighter quarks via weak interaction.



$\mathcal{B}(K^+ \to \pi^0 e^+ \nu_e) = 0.0482$



$\mathcal{B}_{1970}(K^+ \to \pi^+ \nu\bar{\nu}) < 10^{-6}$

- All flavor-changing decays also change electric charge.

  i.e. No evidence of flavor-changing neutral currents.

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

"It has long been an axiom of mine that the little things are infinitely the most important."
Sir Arthur Conan Doyle, (Sherlock Holmes)

$K^+ \to \pi^+ \nu\bar{\nu}$ @ 2nd-order

- Highly Suppressed in SM

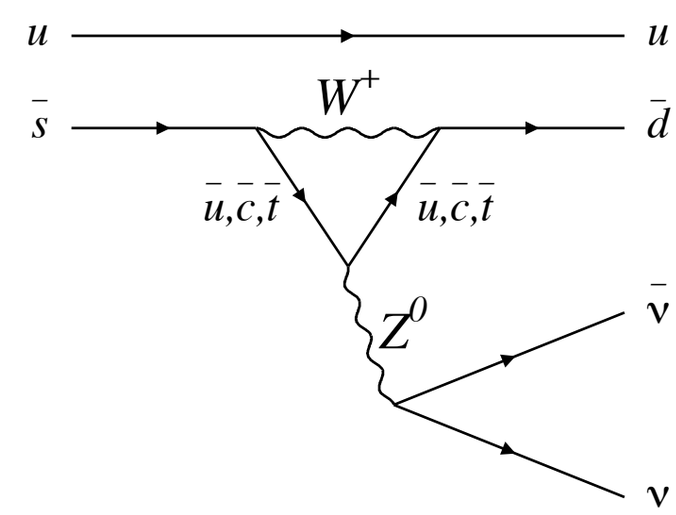
  $m_t >> m_c, m_u$

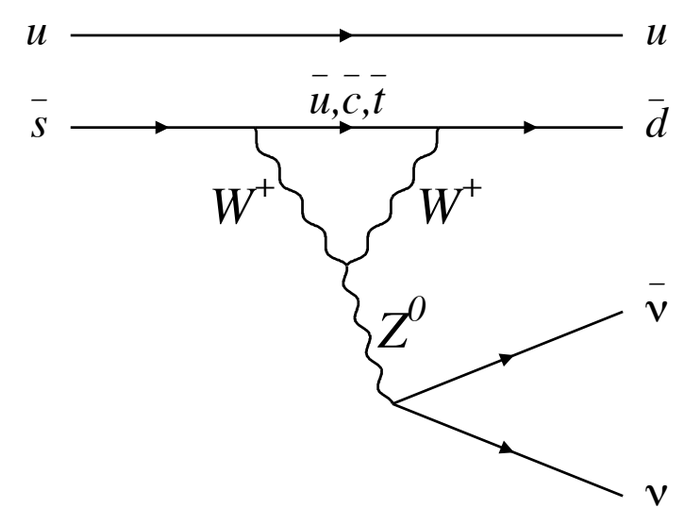
  if $m_t \sim m_c, m_u \implies$ much, much lower BR.

- Theoretically Clean

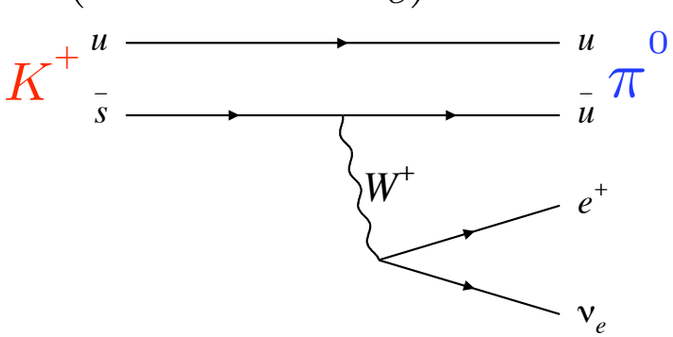
- Branching ratio $\sim 6\%$ precision.

  smaller with NNLO QCD calculation (Buras *et al*)

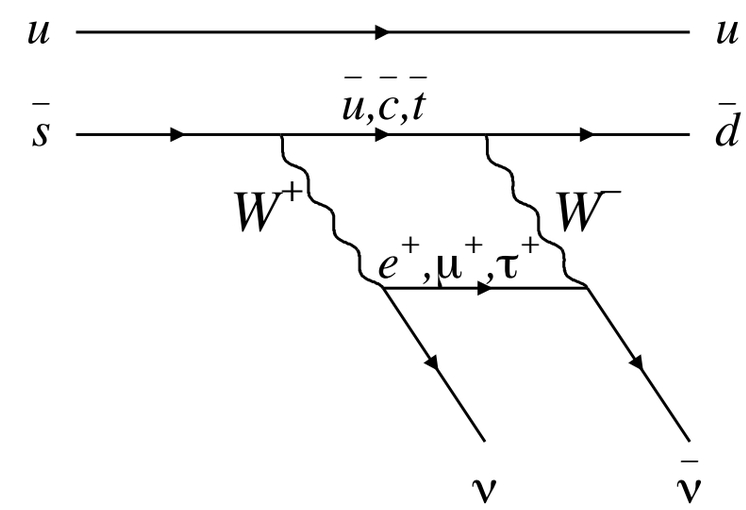




$\mathcal{B}(K^+ \to \pi^0 e^+ \nu_e) = 0.0482$



- Strong interaction of $K^+ \to \pi^+ \nu\bar{\nu}$ is related by isospin by $K^+ \to \pi^0 e^+ \nu$ decay.



FCNC of $K^+ \to \pi^+ \nu\bar{\nu}$ in SM

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |V_{ts}^* V_{td}|^2$

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$

Finding a needle

Claude Monet
Wheatstacks (End of Summer).
1890. Oil on Canvas.
Art Institute of Chicago

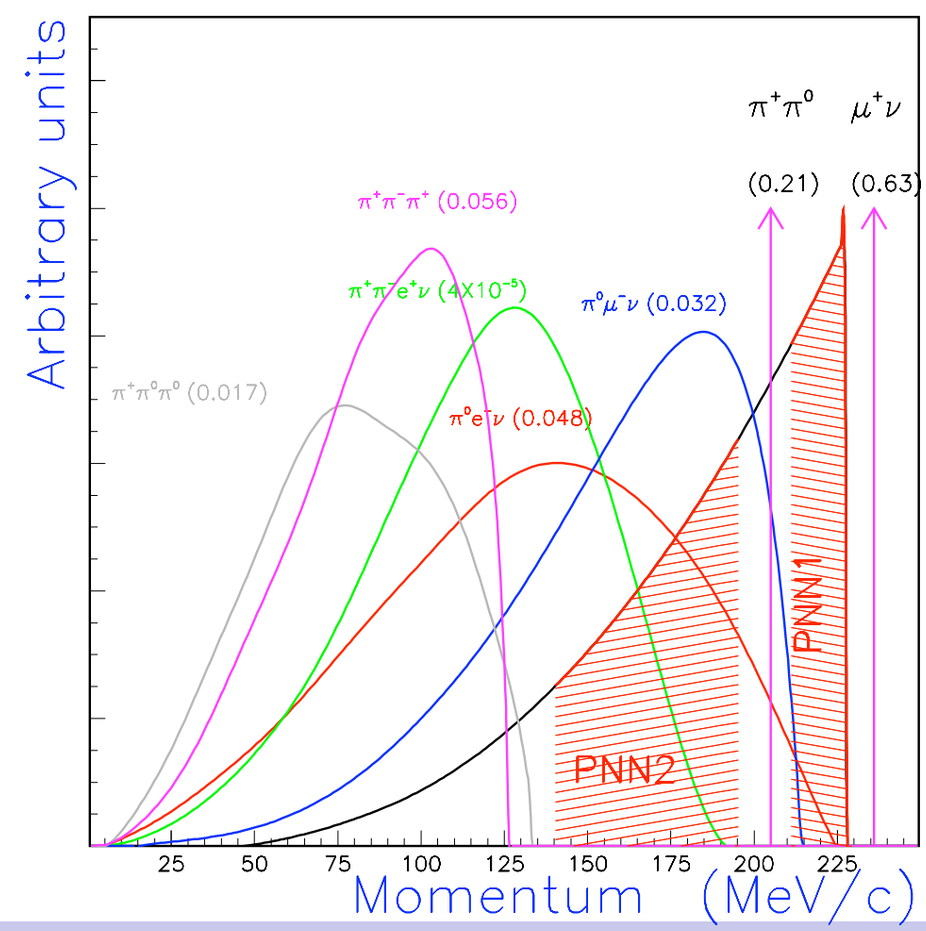
$K^+ \to \pi^+ \nu \bar{\nu}$ Signature

- Entering K^+
- K^+ stopping (Delayed Coincidence)
- Outgoing π^+ track.
- $\nu\ \bar{\nu}$ (not a chance!)

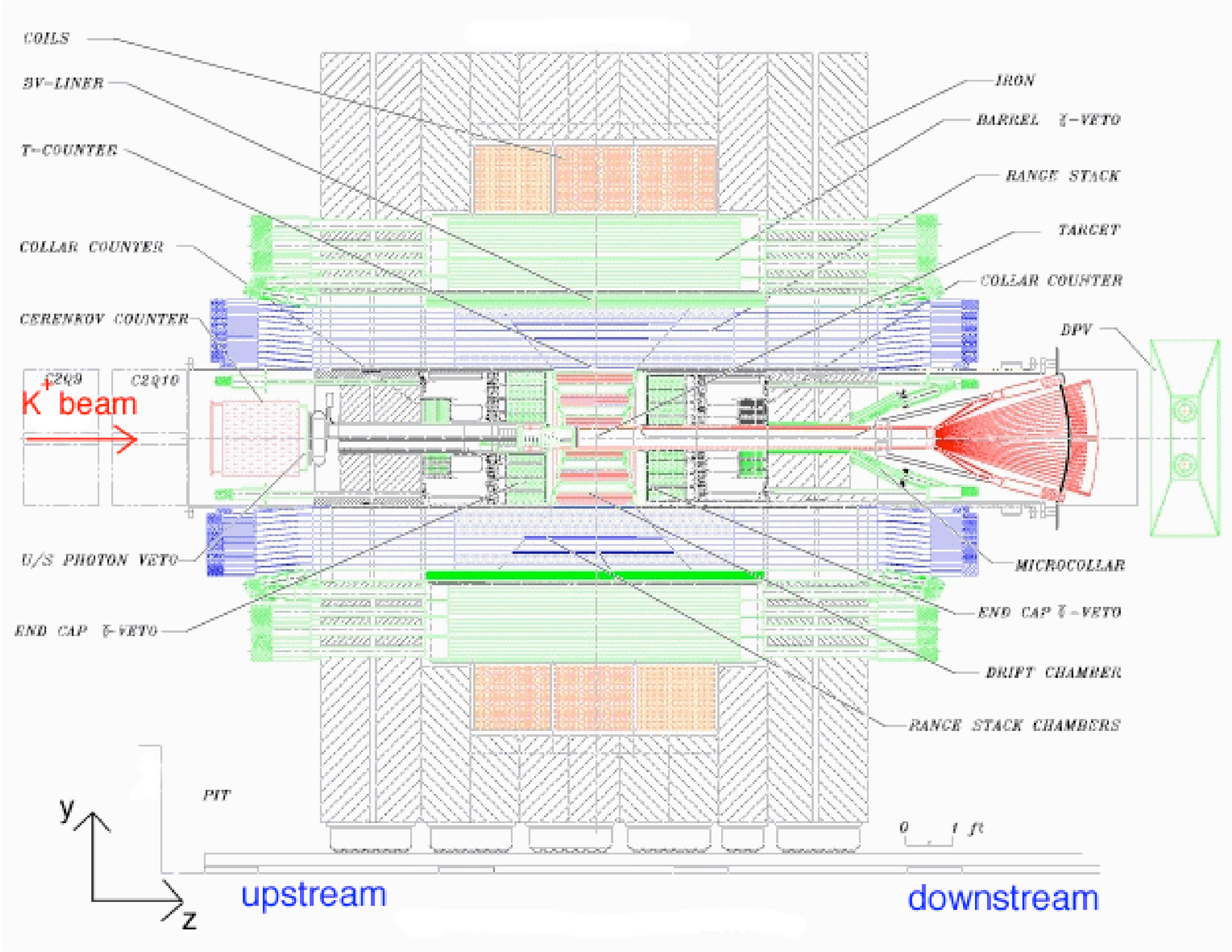
Possible Backgrounds from Decays

Background	Branching Ratio	Track Kin.	Extra Energy	DC	Particle ID	Photons
$K^+ \to \mu^+\nu$	0.6344	X			✓	
$K^+ \to \pi^+\pi^0$	0.2092	X*				✓[2]
$K^+ \to \pi^+\pi^+\pi^-$	0.05590	X	✓			
$K^+ \to \pi^0 e^+\nu$	0.0498				✓	✓[2]
$K^+ \to \pi^0\mu^+\nu$	0.0332				✓	✓[2]
$K^+ \to \pi^+\pi^0\pi^0$	0.01757	X				✓[4]
$K^+ \to \mu^+\nu\gamma$	0.0062				✓	✓
$K^+ \to \pi^+\pi^0\gamma$	0.000275					✓[3]
$K^+ \to \pi^0 e^+\nu\gamma$	0.000269				✓	✓[3]
$K^+ \to \pi^+\pi^+\pi^-\gamma$	0.000104	X	✓			✓
$K^+ \to \pi^+ 3\gamma$	< 0.0001					✓[3]
$K^+ \to e^+\nu\nu\bar{\nu}$	< 0.00006				✓	
$K^+ \to \pi^+\pi^- e^+\nu$	0.0000409		✓			
$K^+ \to \pi^0\mu^+\nu\gamma$	0.000024				✓	✓[3]
$K^+ \to \pi^0\pi^0 e^+\nu$	0.000022				✓	✓[4]
$K^+ \to e^+\nu$	0.0000155	X			✓	
$K^+ \to e^+\nu\gamma$	0.0000152				✓	✓
$K^+ \to \pi^+\pi^-\mu^+\nu$	0.000014		✓			
$K^+ \to \pi^+\pi^0\pi^0\gamma$	0.0000076	X				✓[5]
$K^+ \to \mu^+\nu\nu\bar{\nu}$	< 0.000006				✓	
$K^+ \to \pi^0\pi^0 e^+\nu\gamma$	< 0.000005				✓	✓[4]
$K^+ \to \pi^0\pi^0\pi^0 e^+\nu$	< 0.0000035	X			✓	✓[6]
$K^+ \to \pi^+\gamma\gamma$	0.00000110					✓[2]
$K^+ \to \mu^+\nu\mu^+\mu^-$	< 0.00000041		✓		✓	
$K^+ \to e^+\nu\mu^+\mu^-$	0.000000017		✓		✓	
$K^+ \to e^+\nu e^+ e^-$	0.000000025		✓		✓	
$K^+ \to \mu^+\nu e^+ e^-$	0.000000071		✓		✓	

Background	Branching Ratio	Track Kin.	Extra Energy	DC	Particle ID		Photons	
					Track	Beam	Fid.	Beam
$K^+ n \to K^0 p$	0.000028		✓	✓				
$K^0_L \to \pi^+\mu^-\bar{\nu}$	0.1350		✓	✓				
$K^0_L \to \pi^+ e^-\bar{\nu}$	0.1940		✓	✓				
π-Beam	-			✓		✓		
K-DIF	-			✓	✓*	✓	✓*	
KK-Beam	-		✓		✓*	✓	✓*	
Kπ-Beam	-		✓			✓		
Charged-track scatter in Target								
$K^+ \to \mu^+\nu$	0.6344				✓			
$K^+ \to \pi^+\pi^0$	0.2092		✓					✓[2]
$K^+ \to \pi^+\pi^0\gamma$	0.000275		✓				✓	✓[2]
Charged-track scatter in Range Stack								
$K^+ \to \mu^+\nu$	0.6344	✓[P]			✓			
$K^+ \to \pi^+\pi^0$	0.2092	✓[P]	✓				✓[2]	
$K^+ \to \pi^+\pi^0\gamma$	0.000275		✓				✓[3]	



E949 Detector



K^+ beam

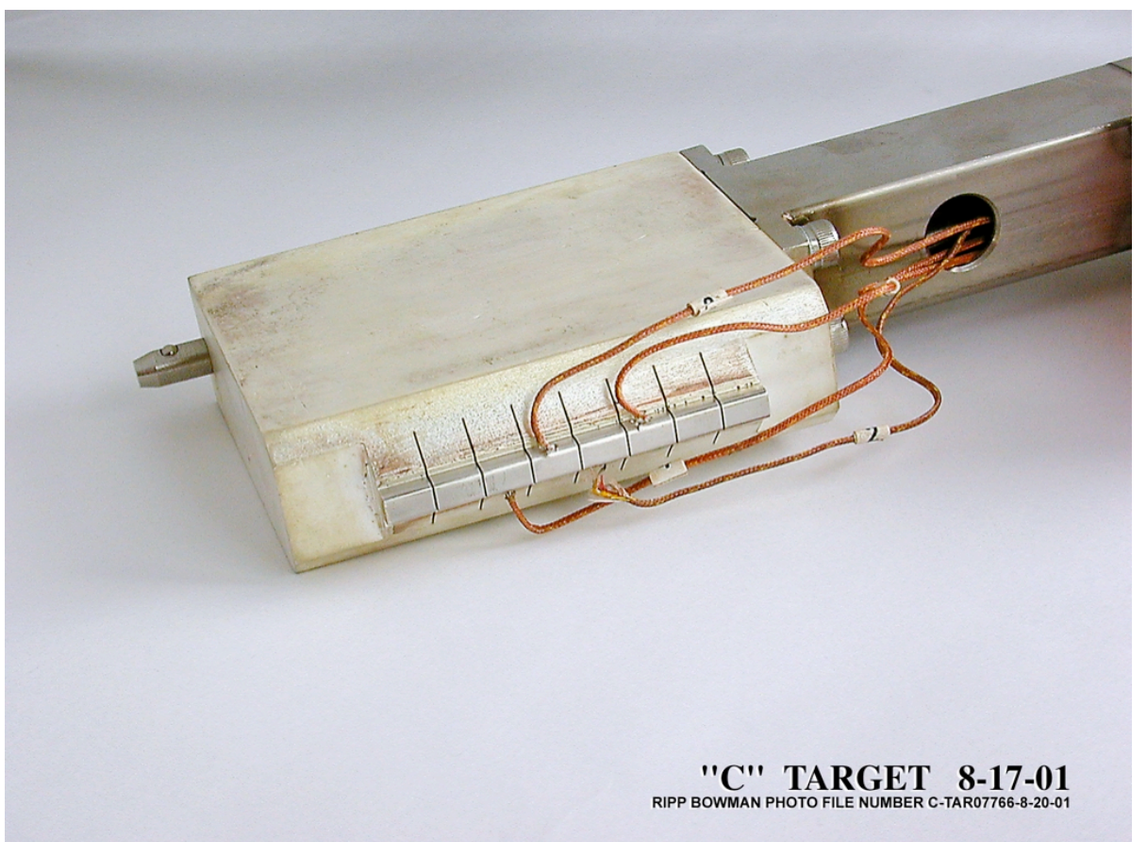
- 65×10^{12} @ 24 GeV/c Protons on production target

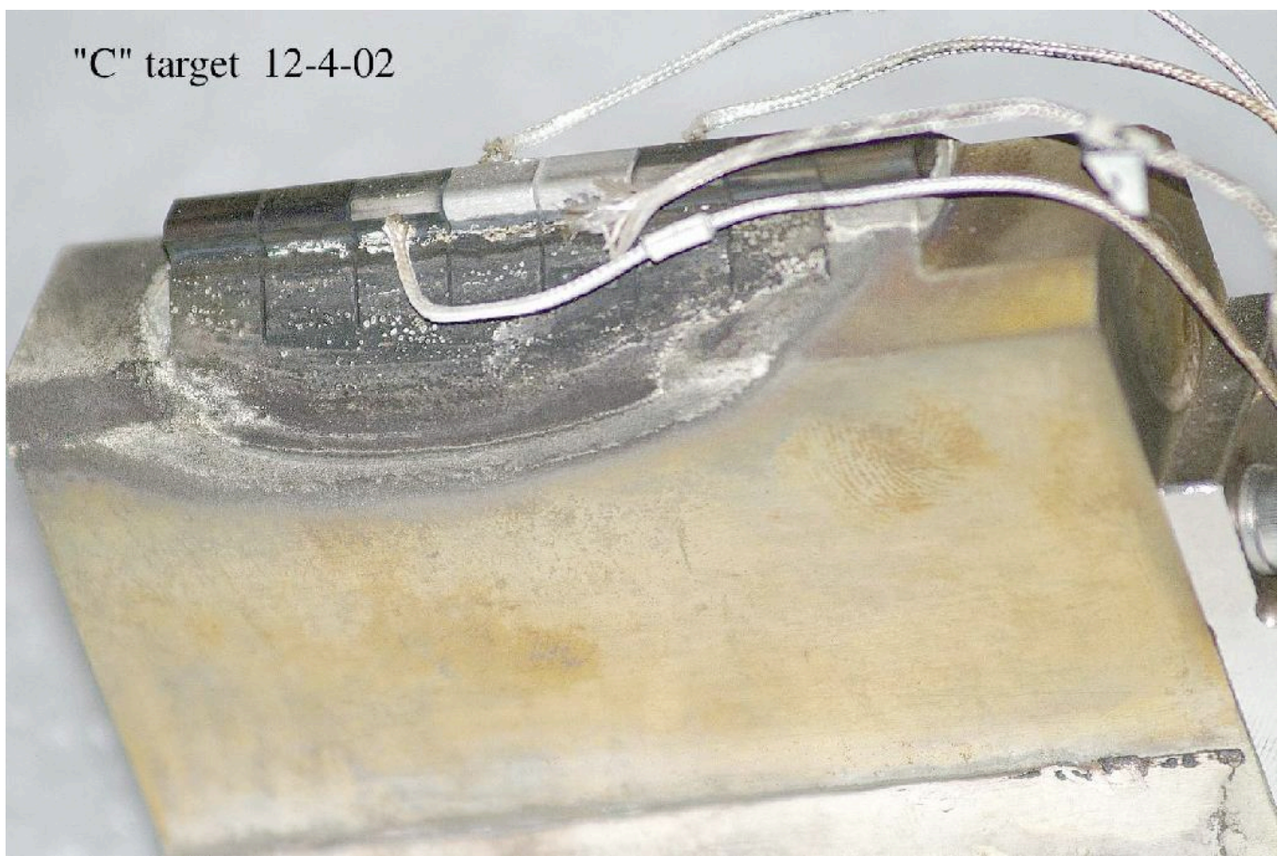
  2 sec 'spill' every 5 sec

  3.5×10^6 K^+ per spill

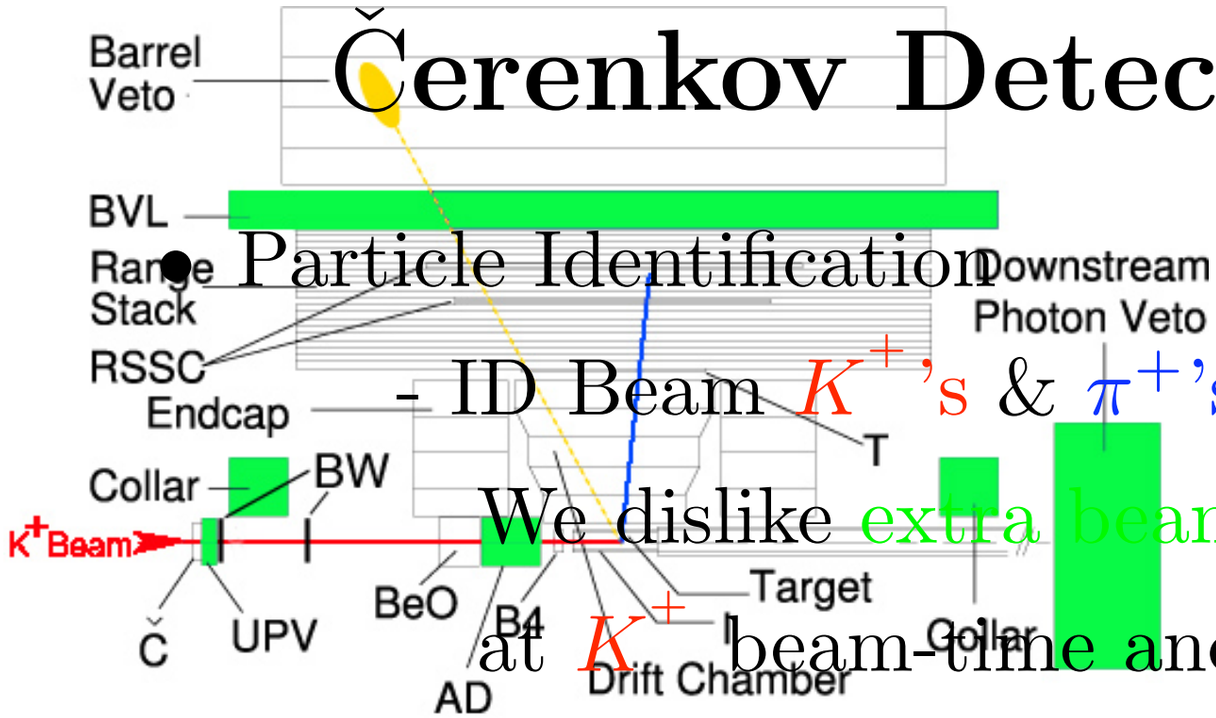
- Electrostatic Separators $\Longrightarrow$ K^+ : π^+ of 4:1

  Not working 3:1





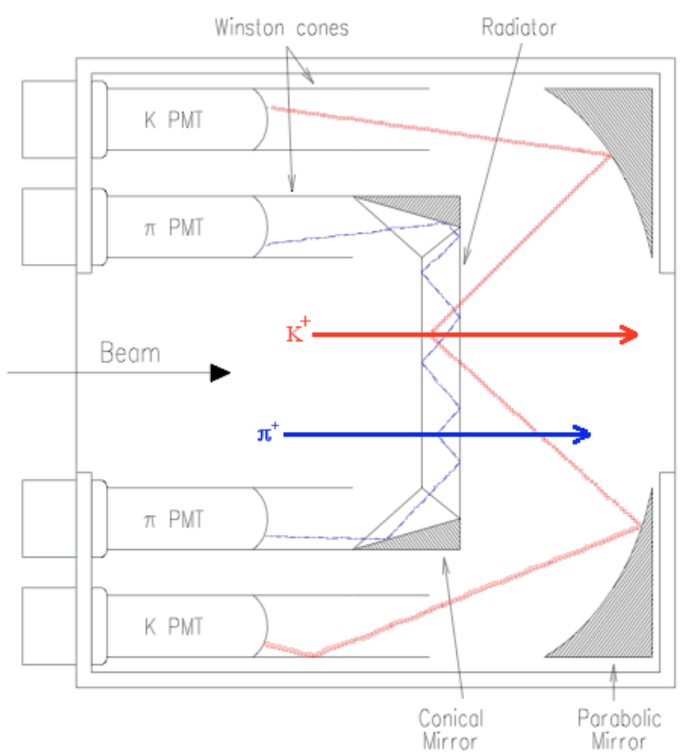
Detecting the K^+ beam

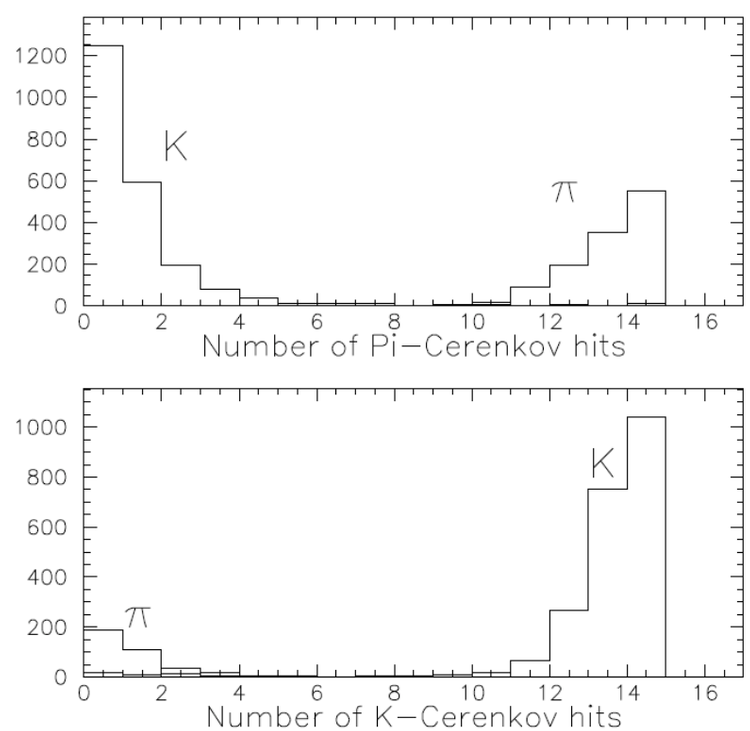


Čerenkov Detector

- Particle Identification
  - ID Beam K^+'s & π^+'s.
  - We dislike extra beam particles at K^+ beam-time and decay-time.
- Counts total # of K^+

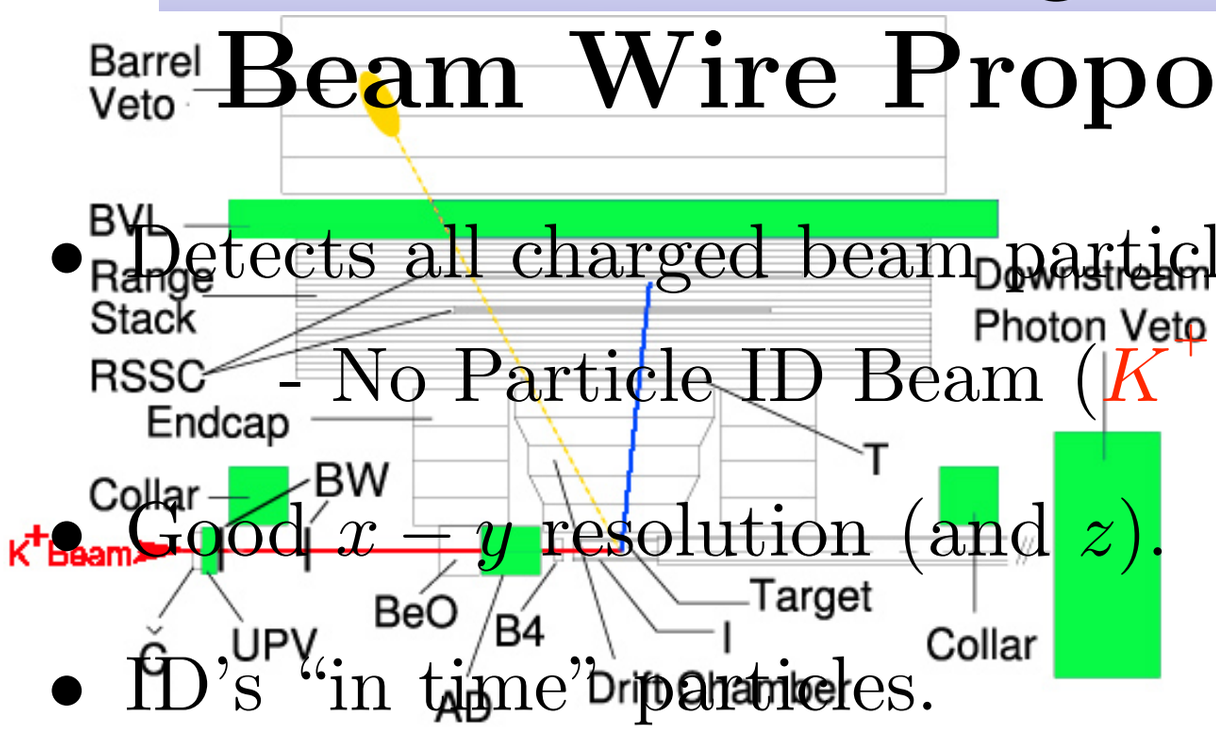
Čerenkov Detector





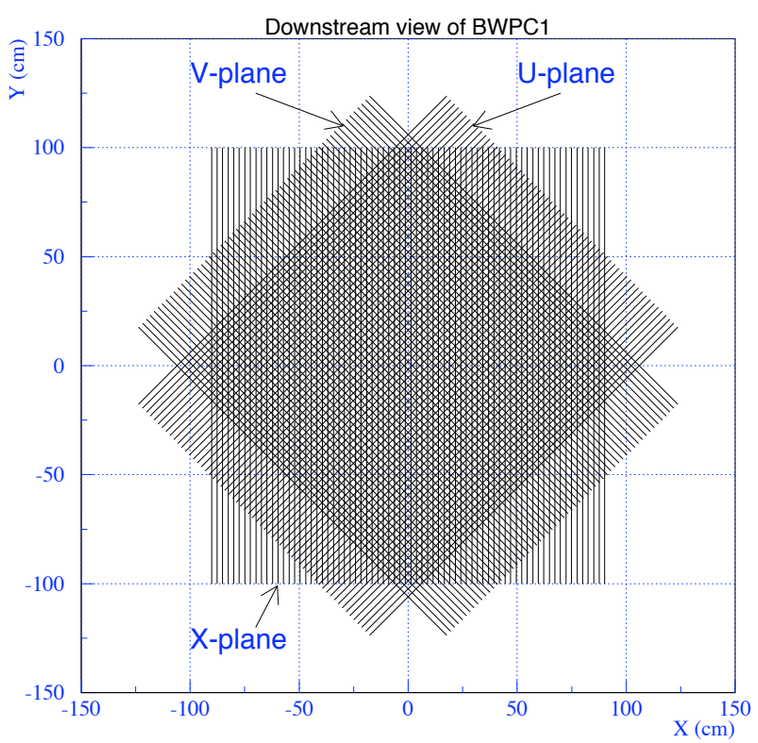
Detecting the K^+ beam

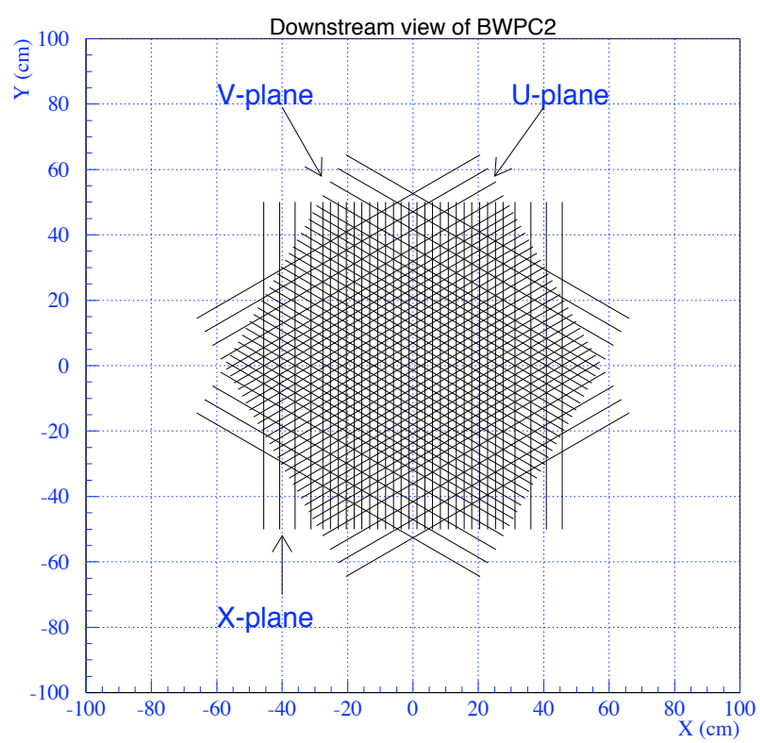
Beam Wire Proportional Chambers



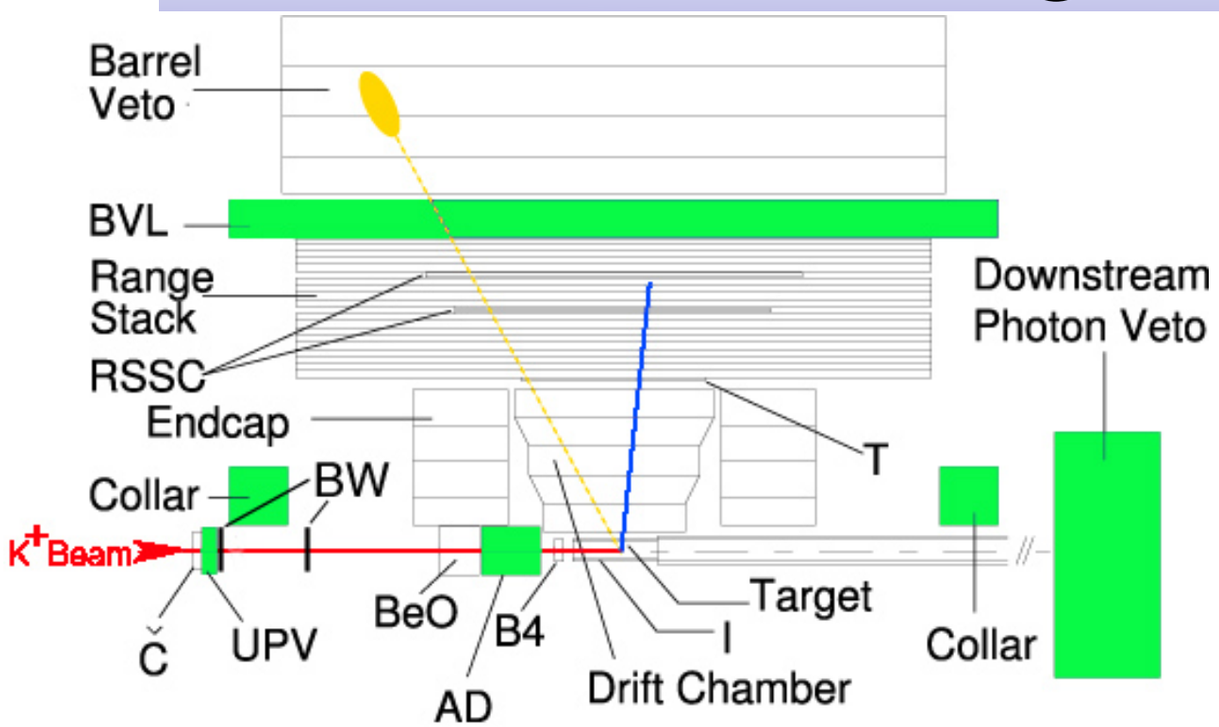
- Detects all charged beam particles.
  - No Particle ID Beam (K^+ or π^+?).
- Good $x - y$ resolution (and z).
- ID's "in time" particles.

Beam Wire Proportional Detectors

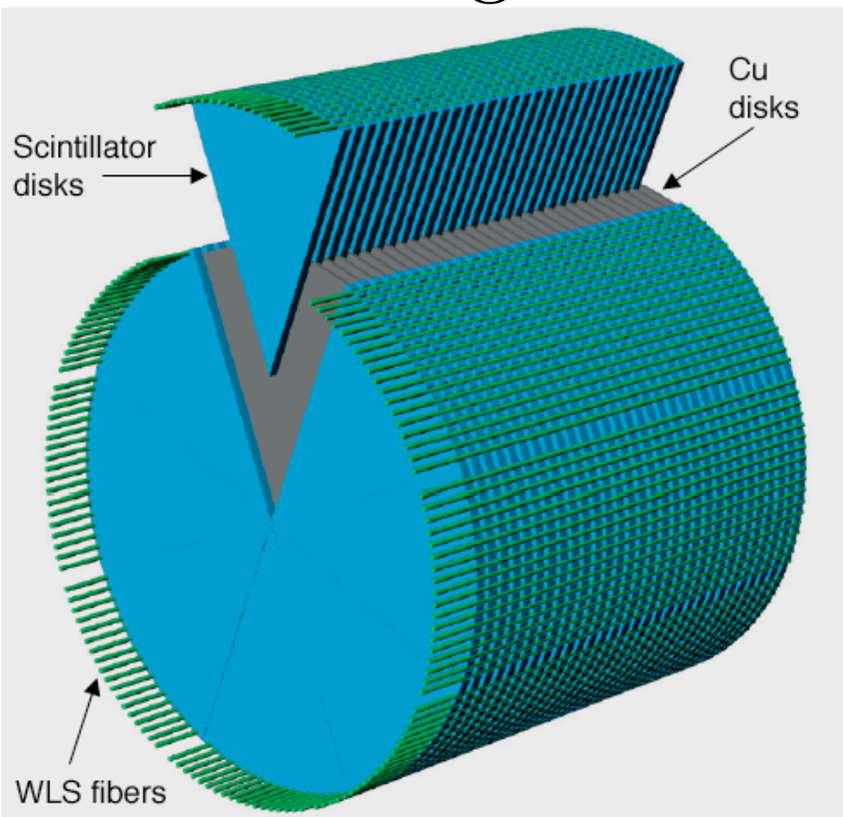




Detecting the K^+ beam



Active Degrader



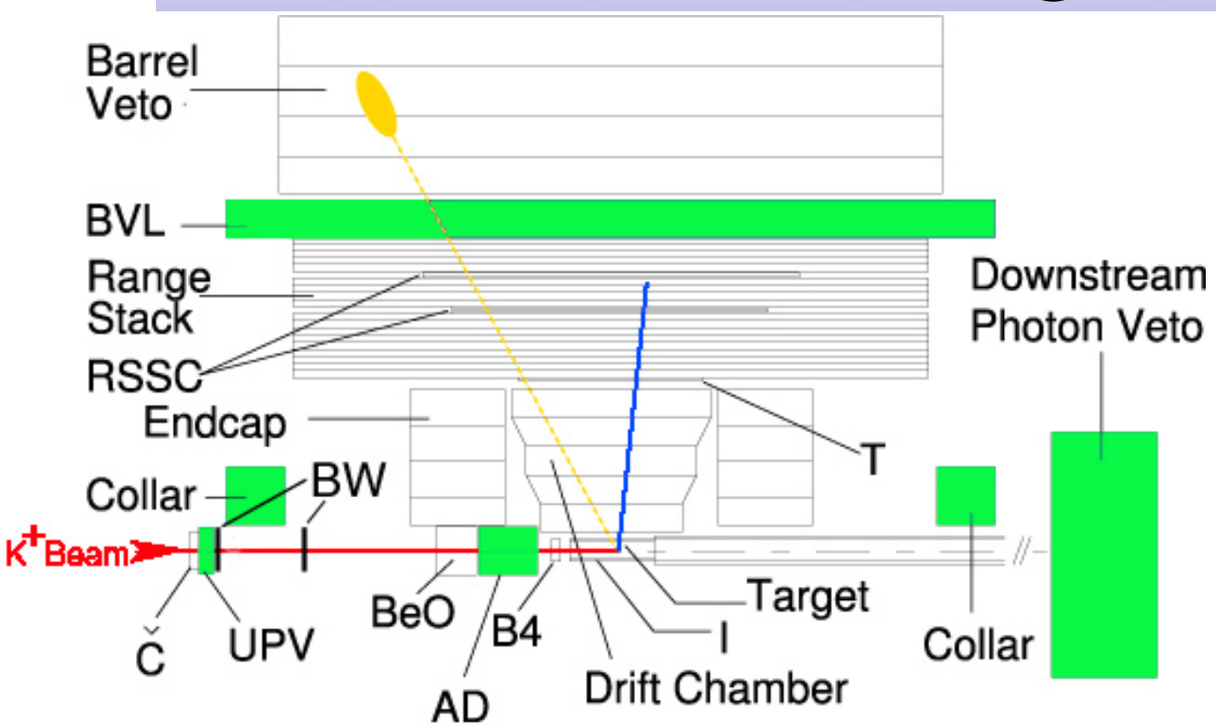
Inactive Degrader

- Made of BeO.
- Slows down K^+'s

Active Degrader

- Slows down K^+'s
- Measures deposited energy.
- Poor $x - y$ resolution.
- Not used to ID additional beam time particles.

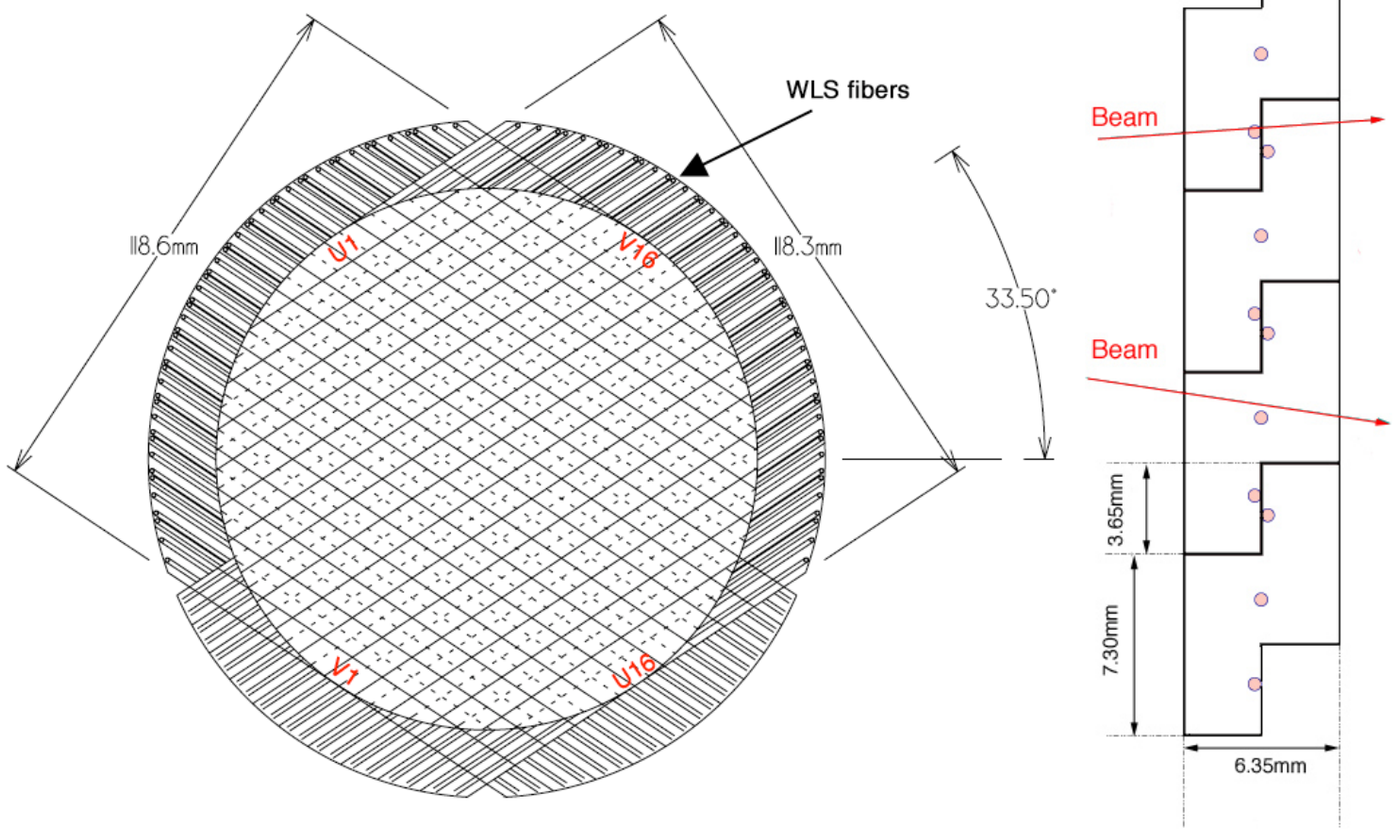
Detecting the K^+ beam



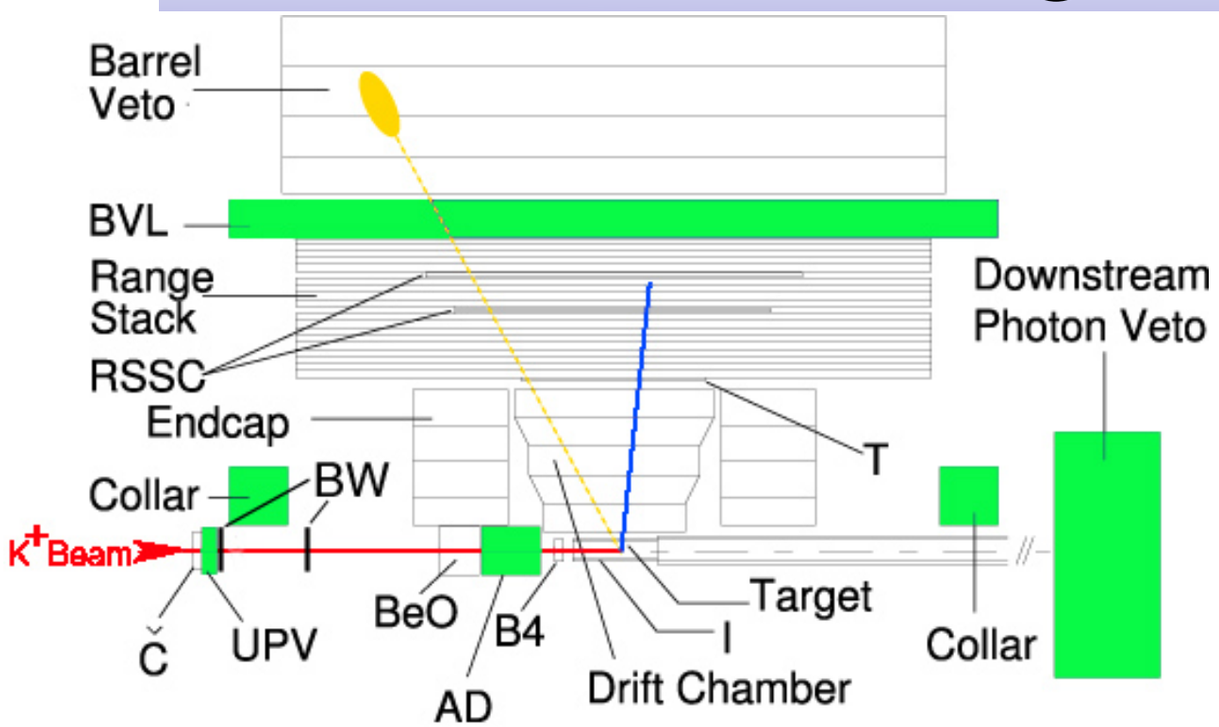
B4 Hodoscope

- Two orthogonal planes of "fingers"
  - Good $x - y$ resolution.
  - Matching with Target region.
- Particle Identification
  - via $\frac{dE}{dX}$

B4 Hodoscope



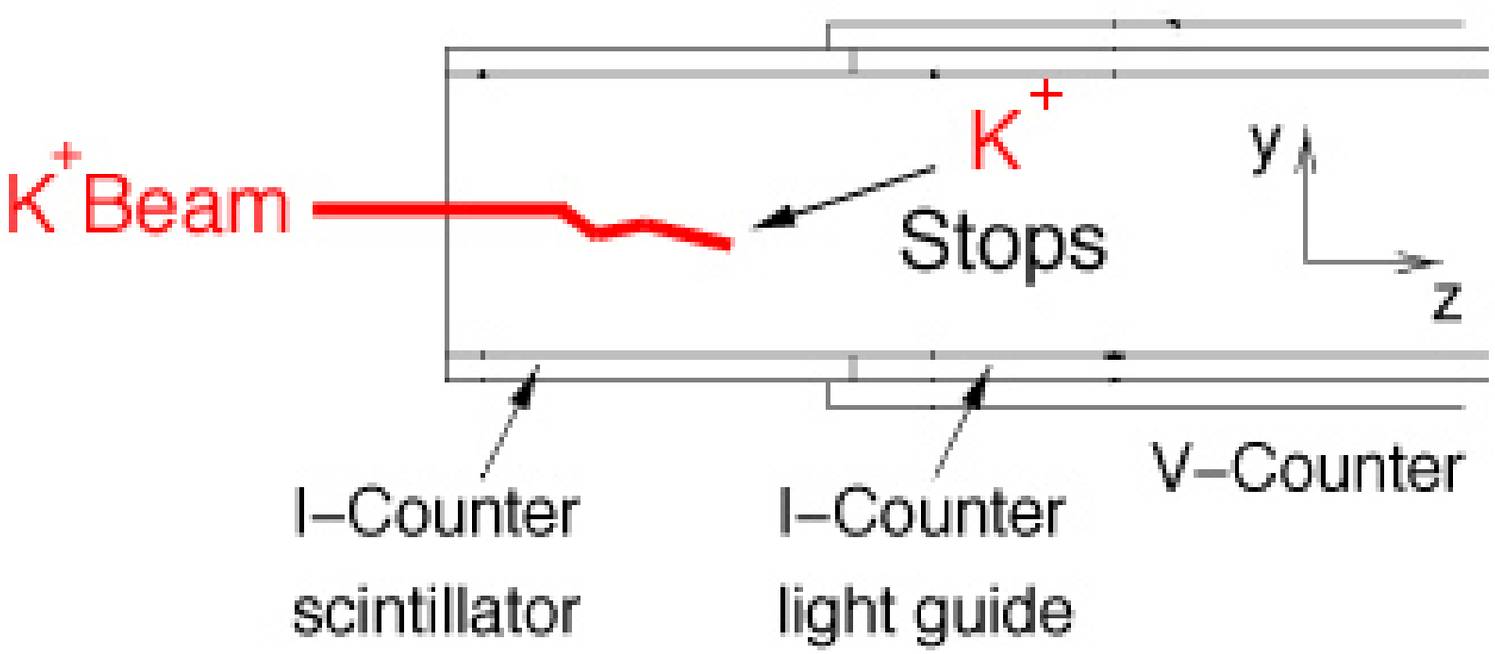
Detecting the K^+ beam



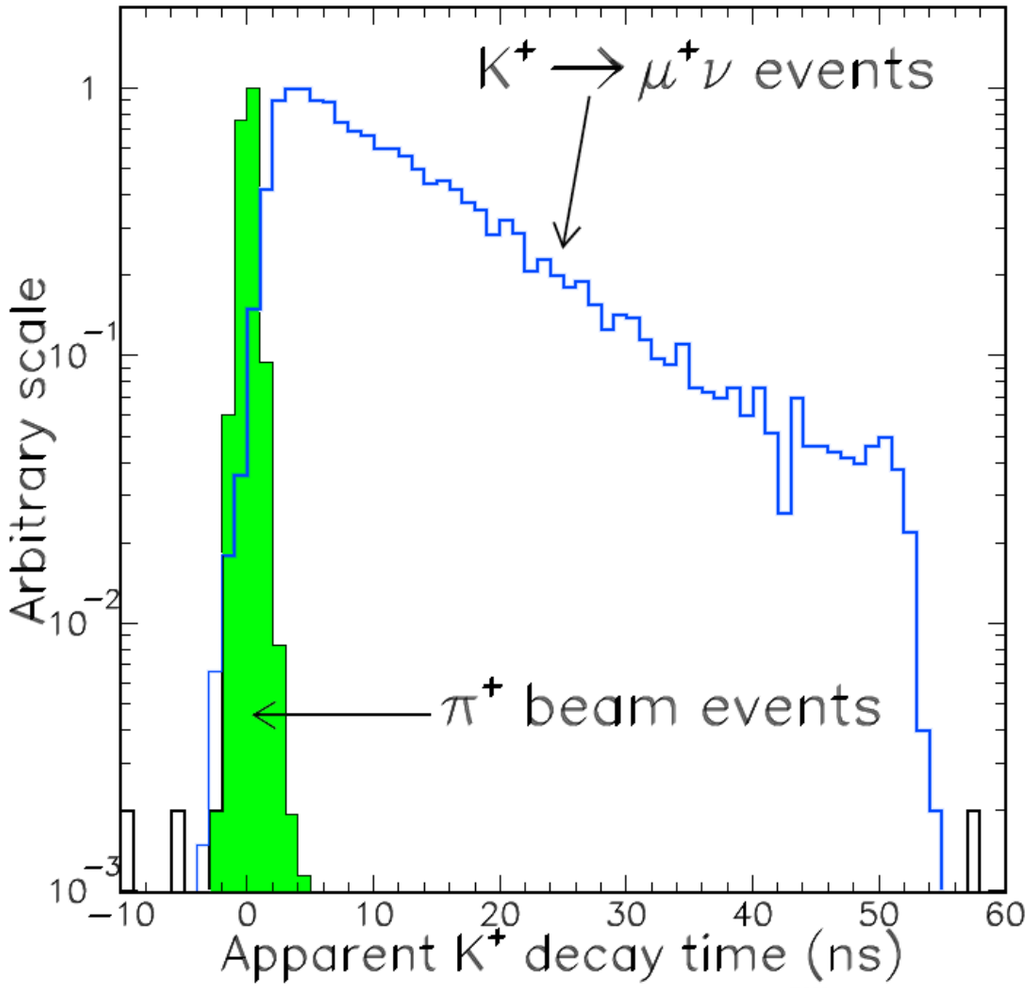
Target

- ~ 500 scintillating fibers (0.5 mm-square)
  - Good $x - y$ resolution.
  - Poor z resolution.
- K^+ stops here (ideally!)
  - $\sim 10 - 60$ MeV$/fiber$

Target



Delayed Coincidence



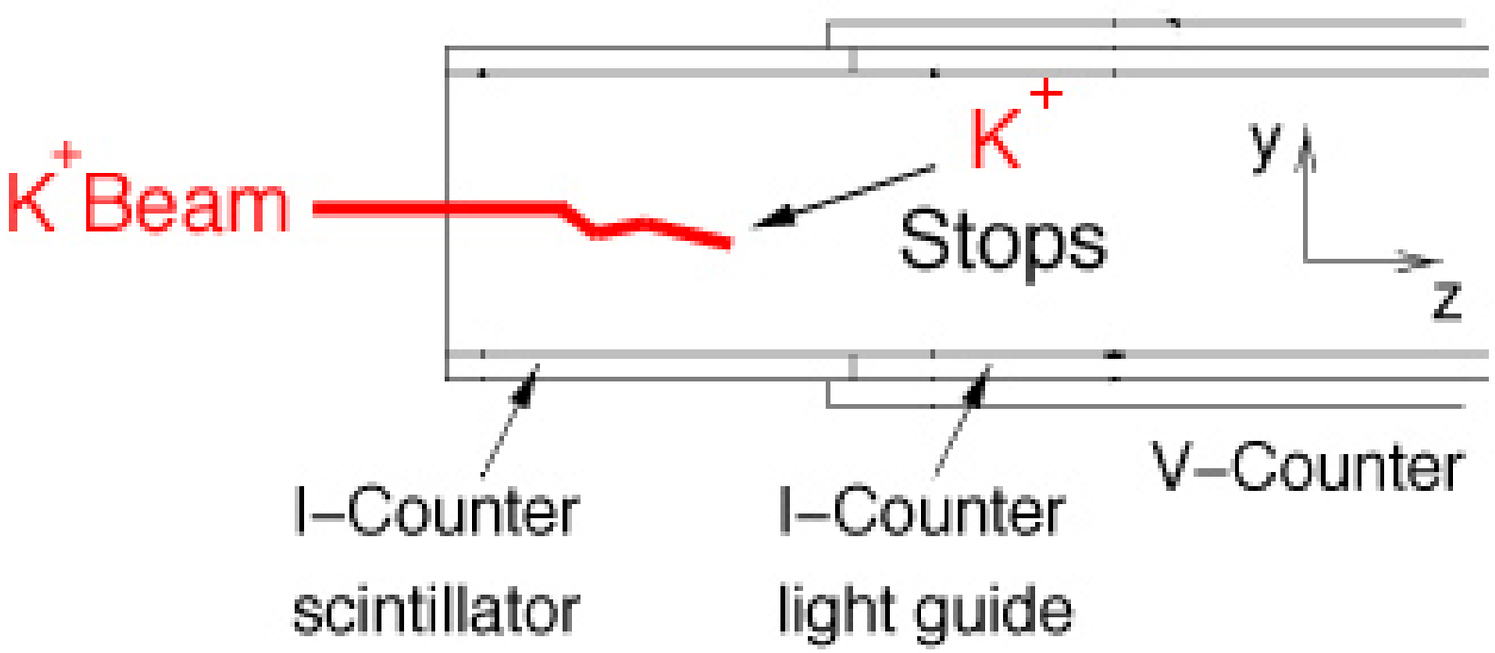
- Wait for K^+ to decay (> 2 ns)

  Time difference between incoming K^+ and outgoing π^+

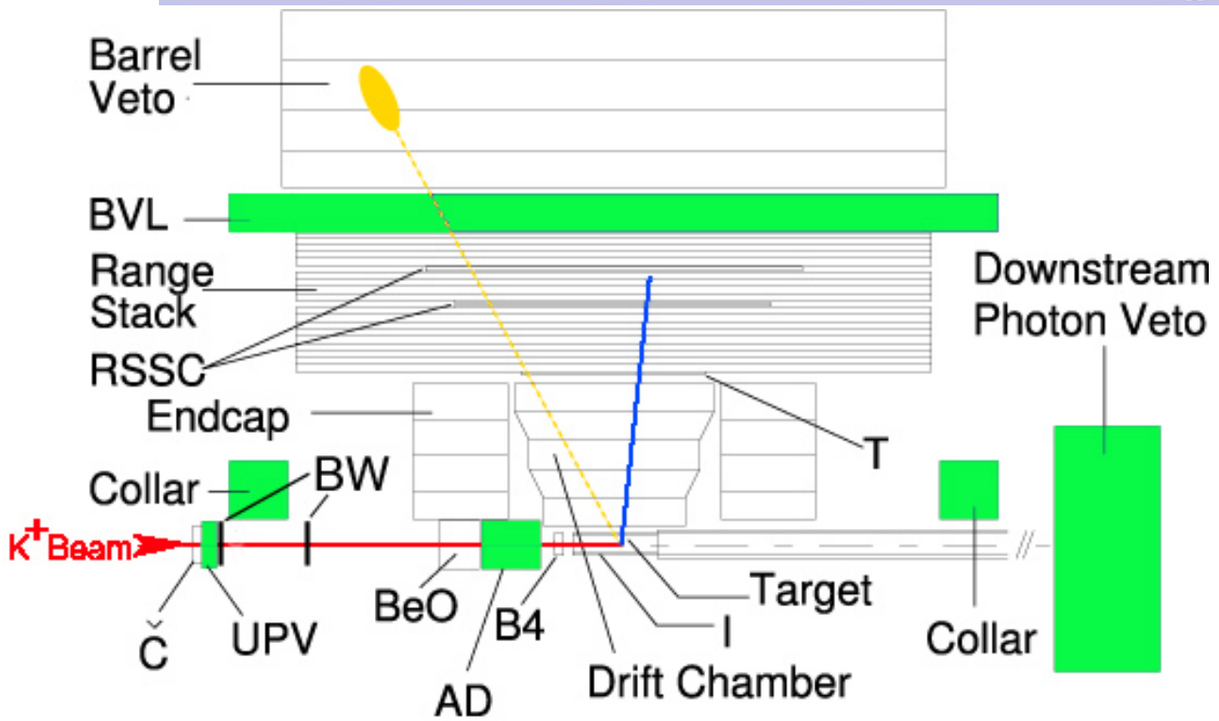
- Removes Beam Background

  Decay-in-flight background

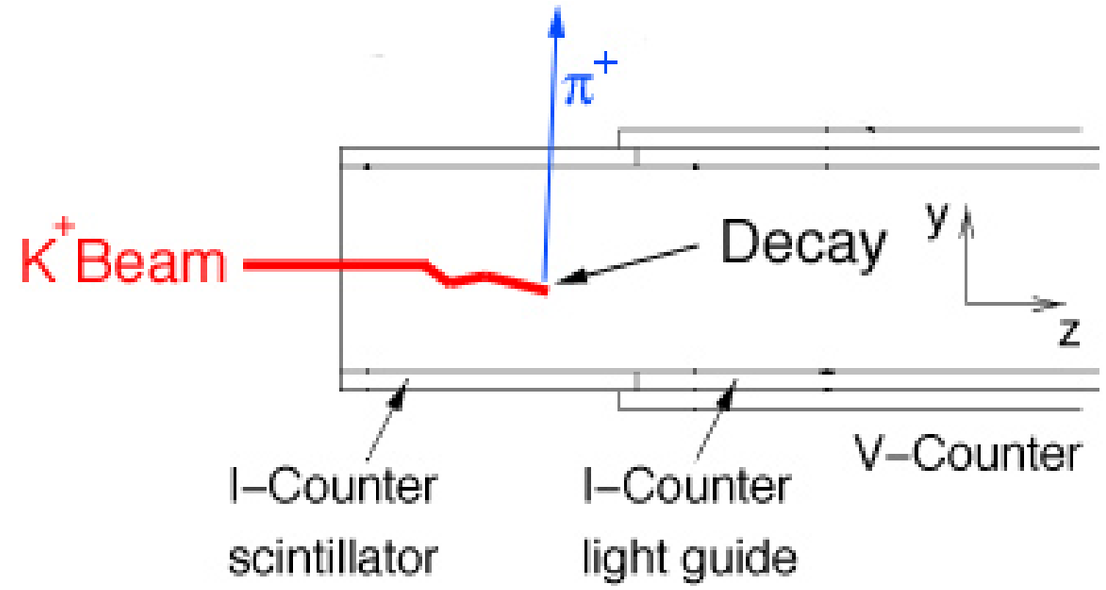
  π^+-beam scatters



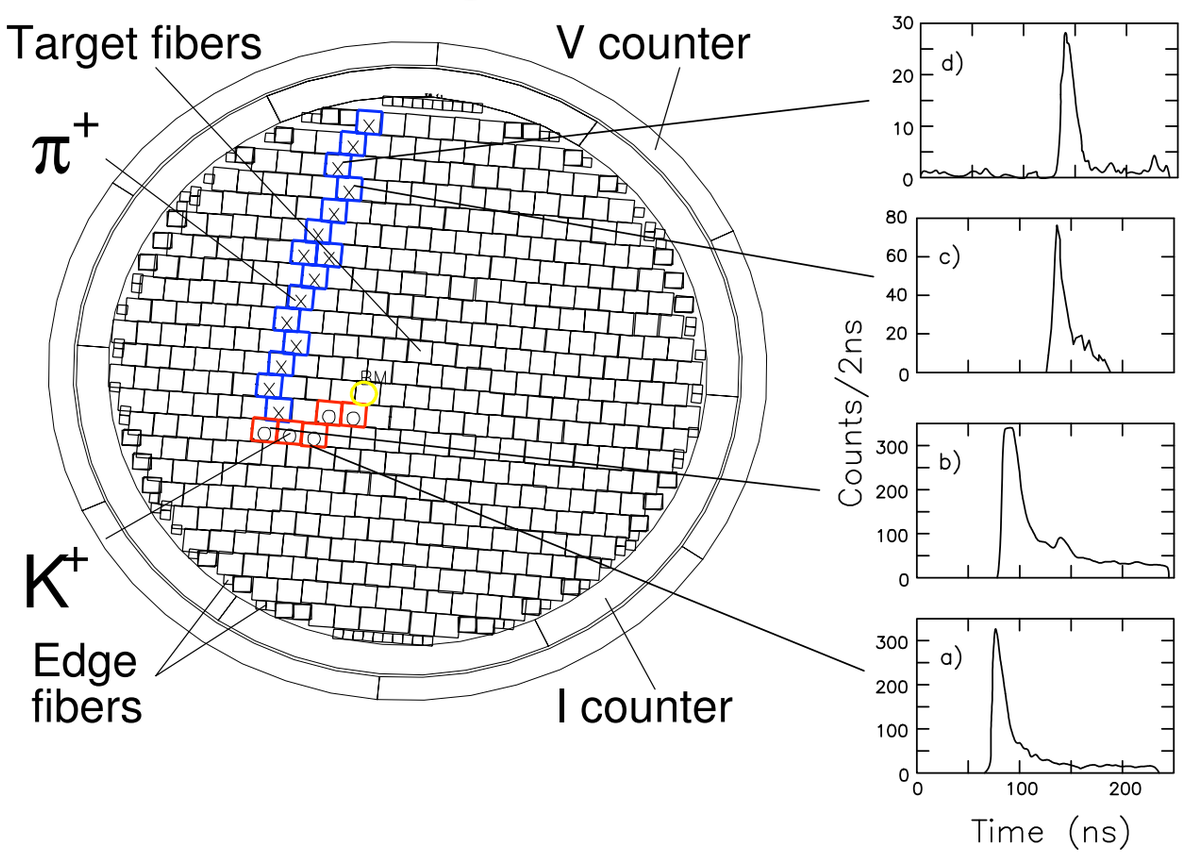
Detecting the π^+



Target

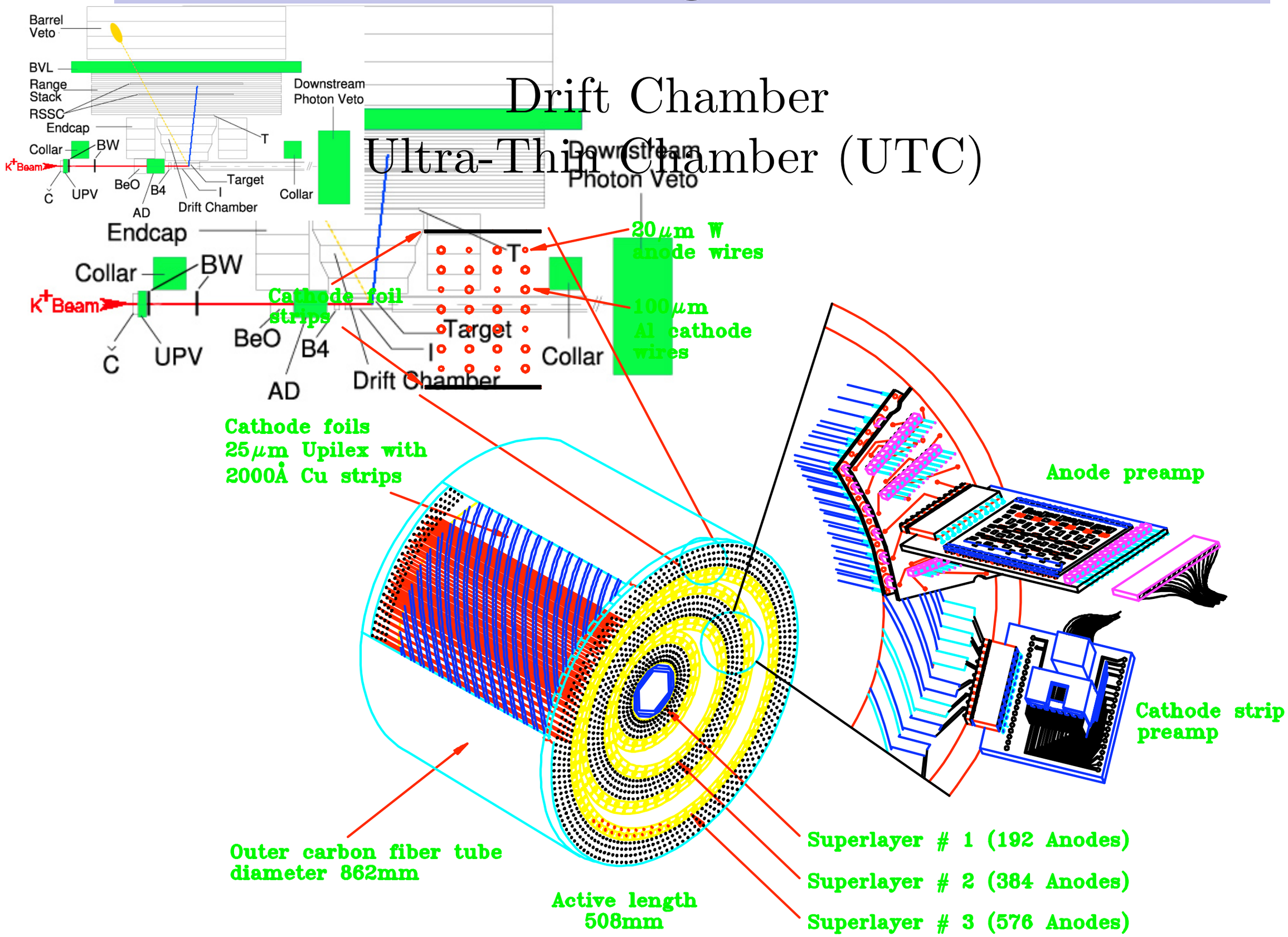


Target

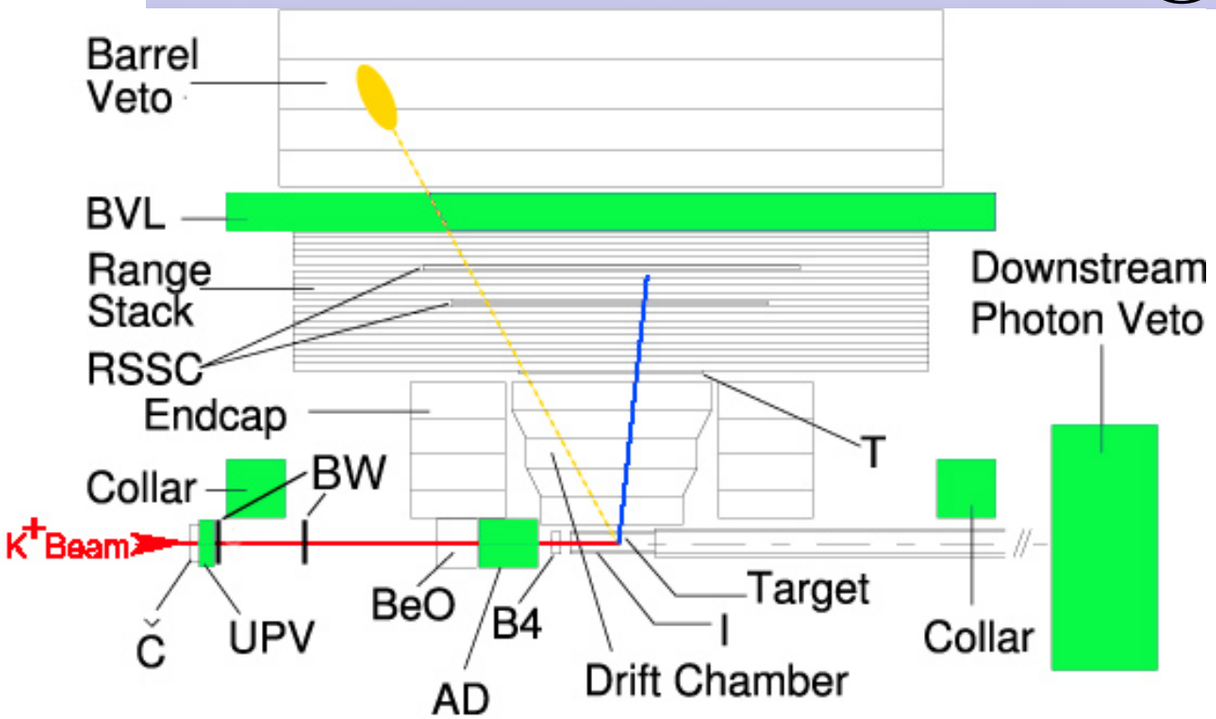


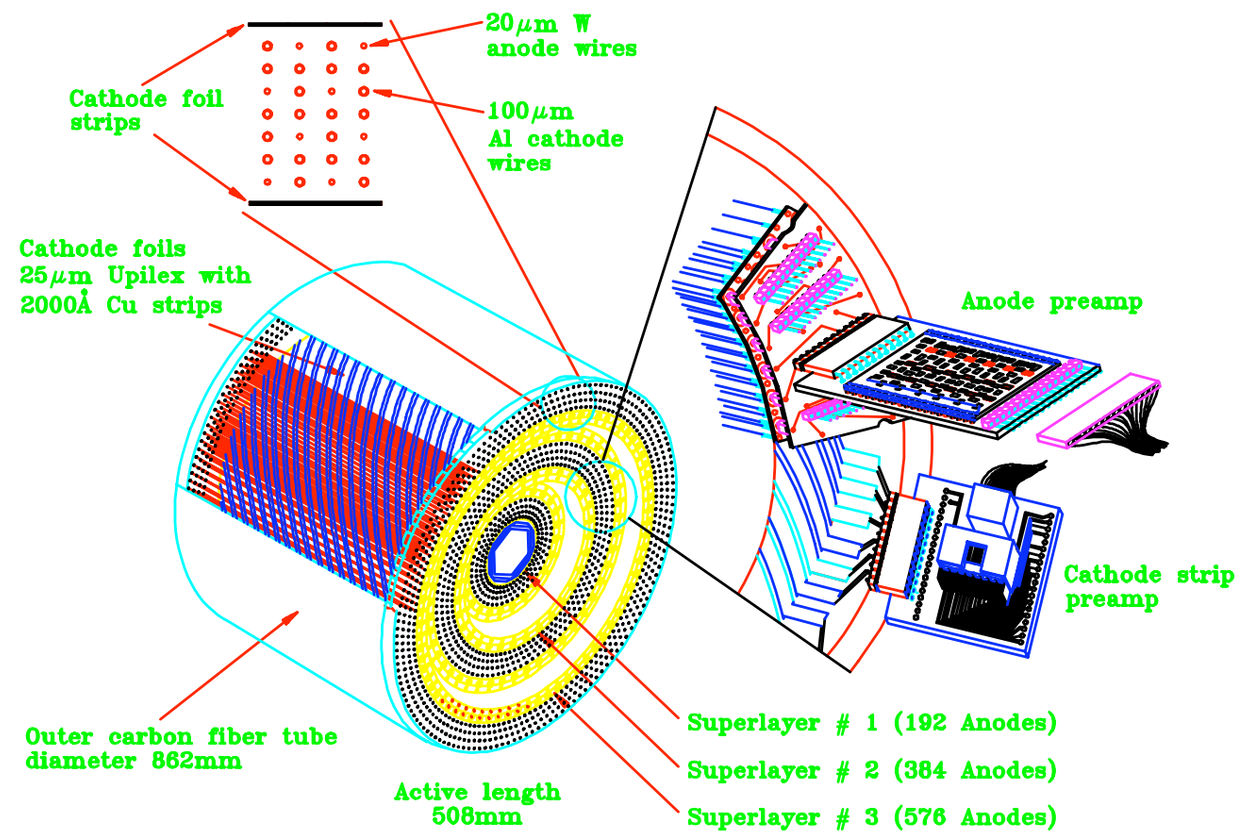
- π^+ Decays
  - Minimum ionizing particle
  - $\sim 0.1 - 1.5$ MeV/*fiber*
- I(don't know what I means)-Counter
  - Trigger on outgoing charged track
  - Defines fiducial region
- V(eto)-Counter
  - Vetoes charged tracks outside fiducial region

Detecting the π^+



Detecting the π^+





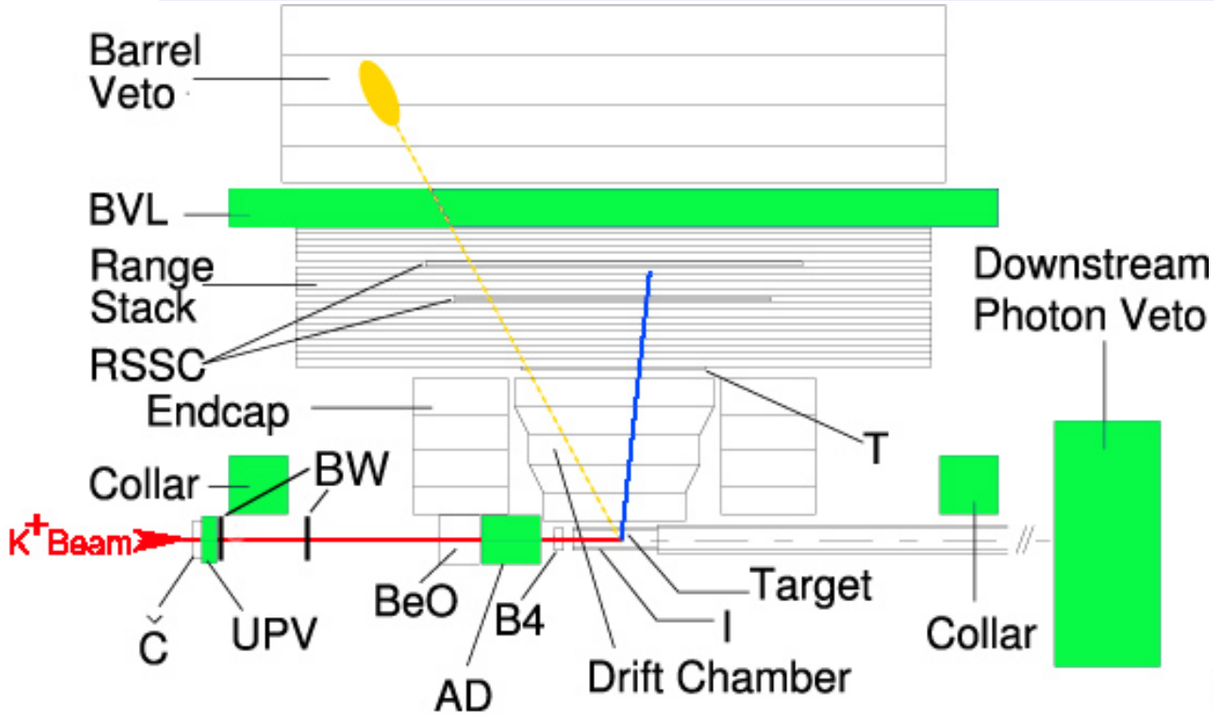
UTC

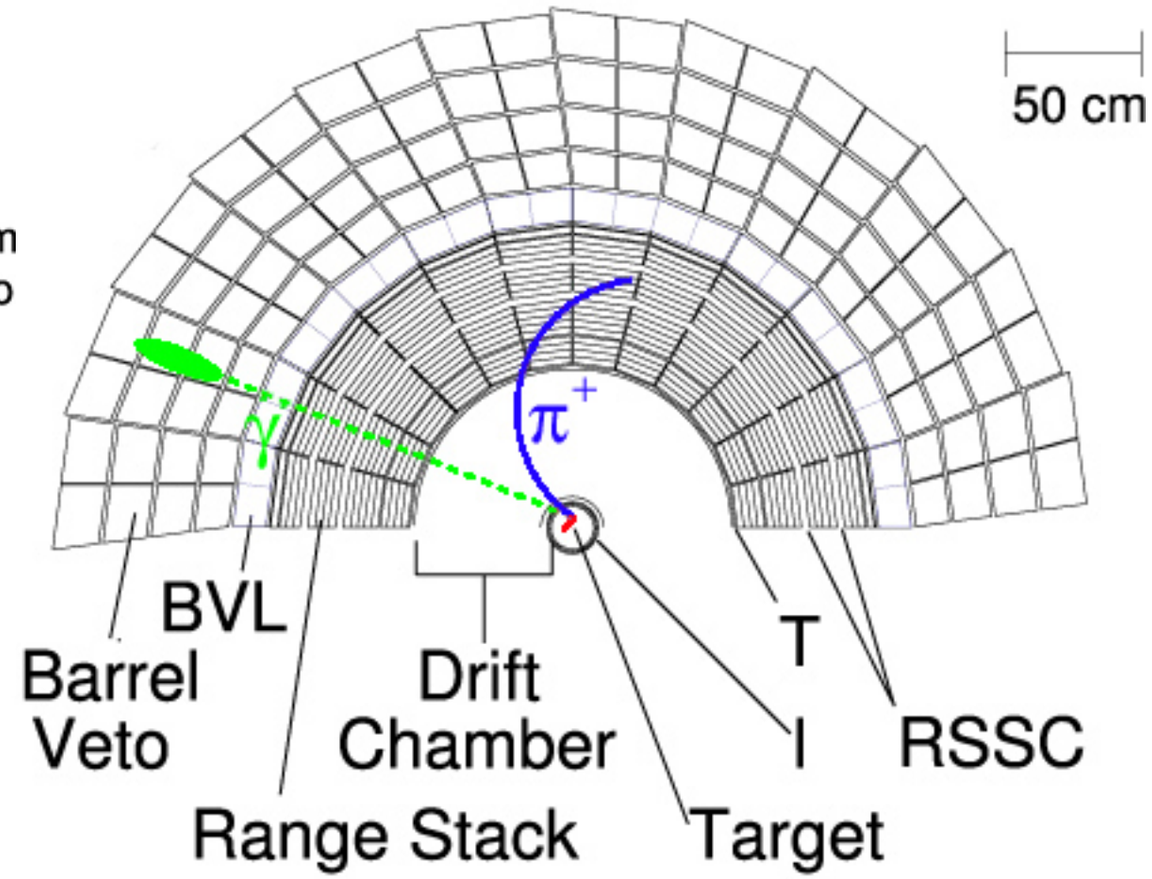
- Detects charged tracks
- ~~Very~~ ^{Ultra} Thin Chamber

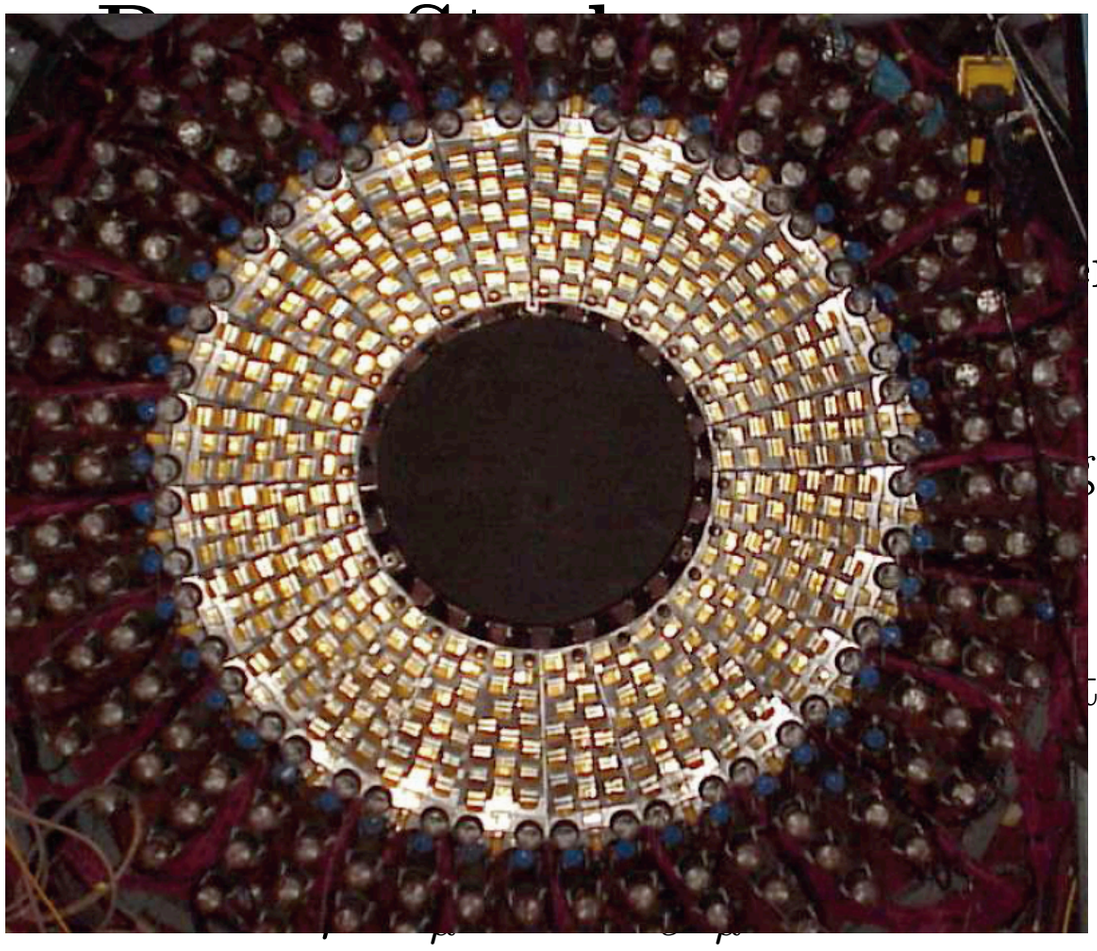
  Low chance of γ converting

  Small energy loss in charged track
- Good $x - y - z$ resolution
- Track matching between Target & Range Stack (next)

Detecting the π^+

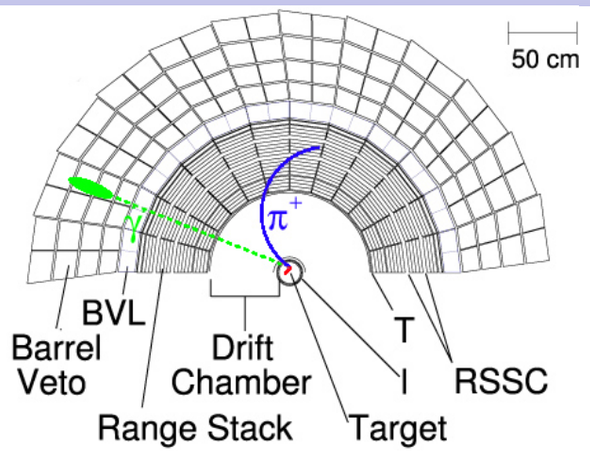




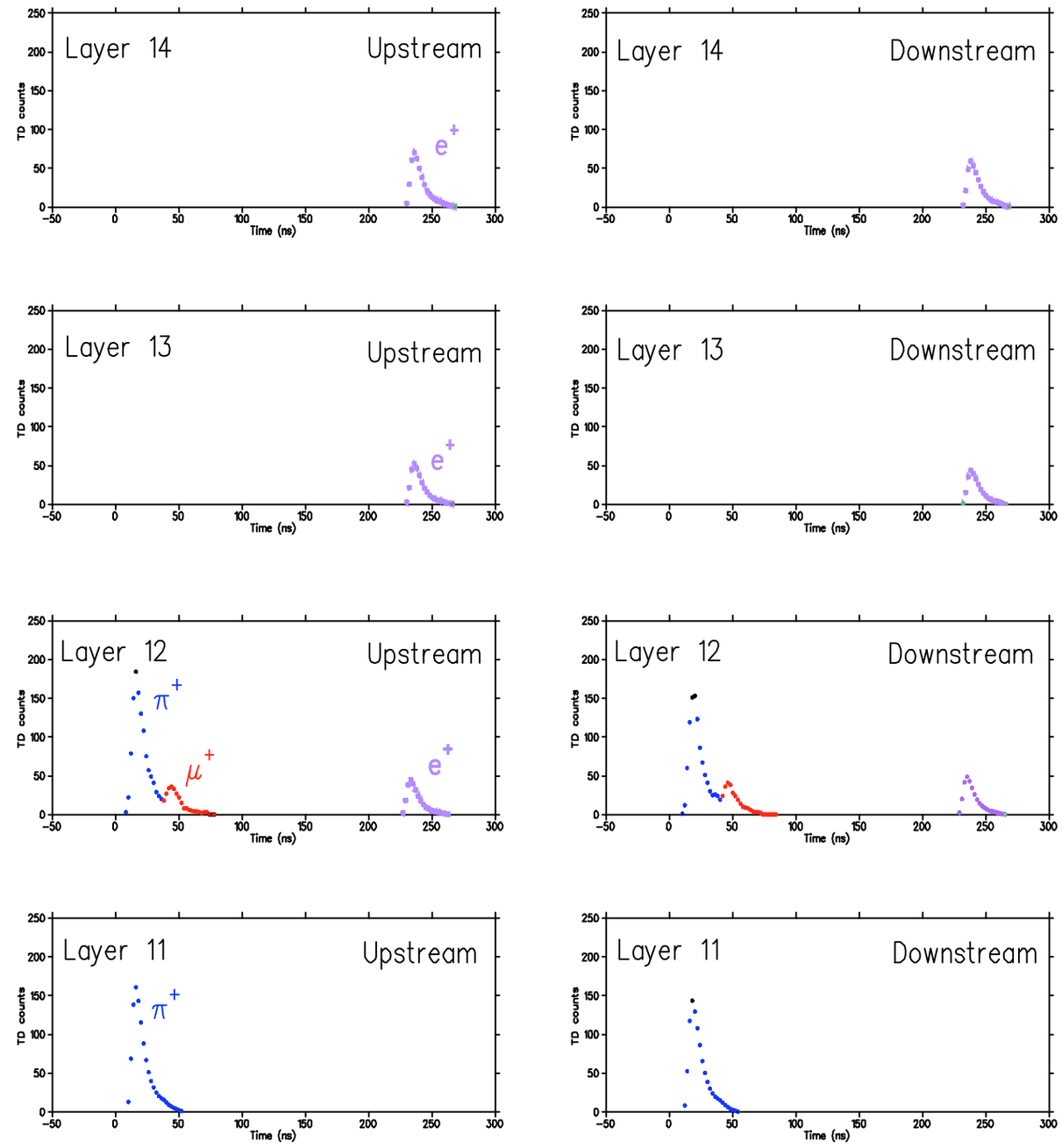


- r (0.635 cm)
- gion
- track

Detecting the π^+



$$\pi^+ \to \mu^+\nu_\mu \to e^+\bar{\nu}_e\nu_\mu$$



- ID $\pi^+ \to \mu^+\nu_\mu \to e^+\bar{\nu}_e\nu_\mu$
- Sample pulse height

  Every 2 ns for 2 μs

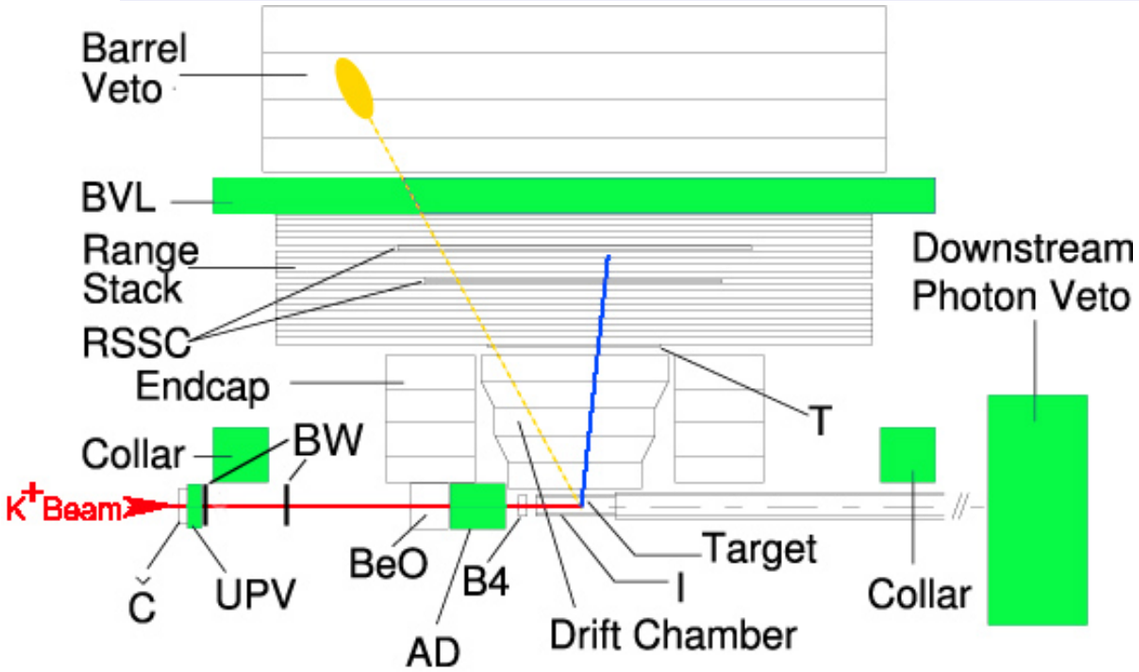
  TDC's for 10 μs
- $\pi^+ \to \mu^+$

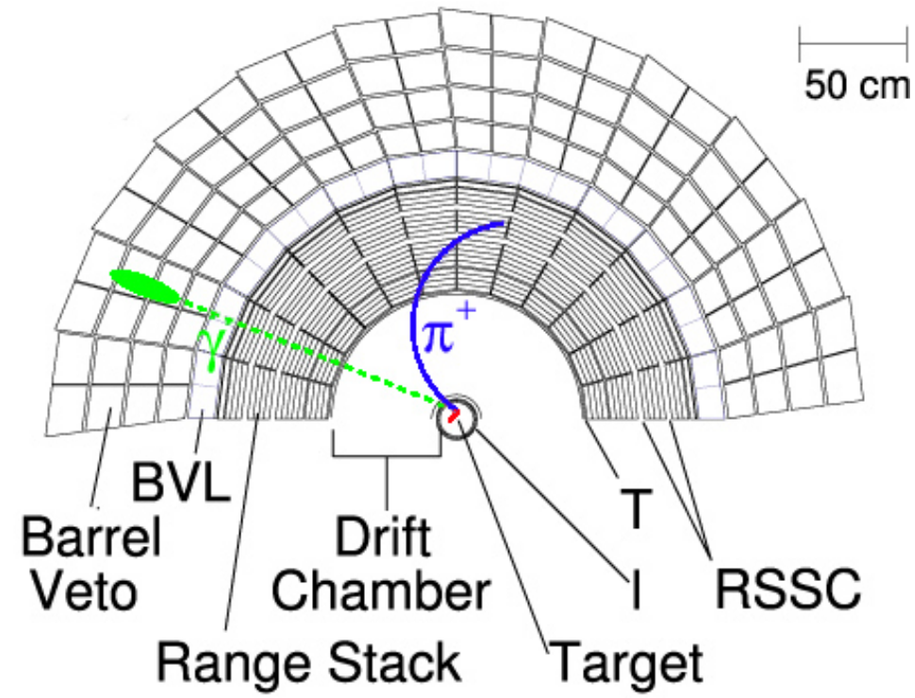
  $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm,

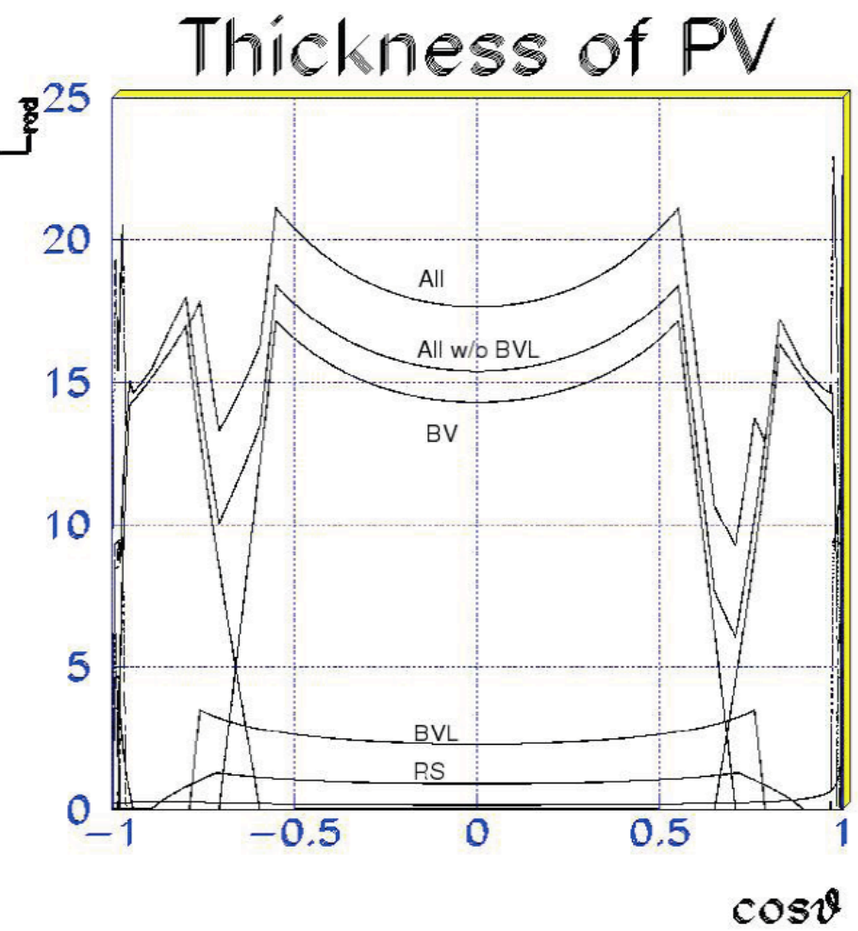
  $\tau_\pi = 26.0$ ns
- $\mu^+\nu_\mu \to e^+\bar{\nu}_e\nu_\mu$

  $E_e \leq 53$ MeV, $\tau_\mu = 2.2$ μs

Detecting the γ's





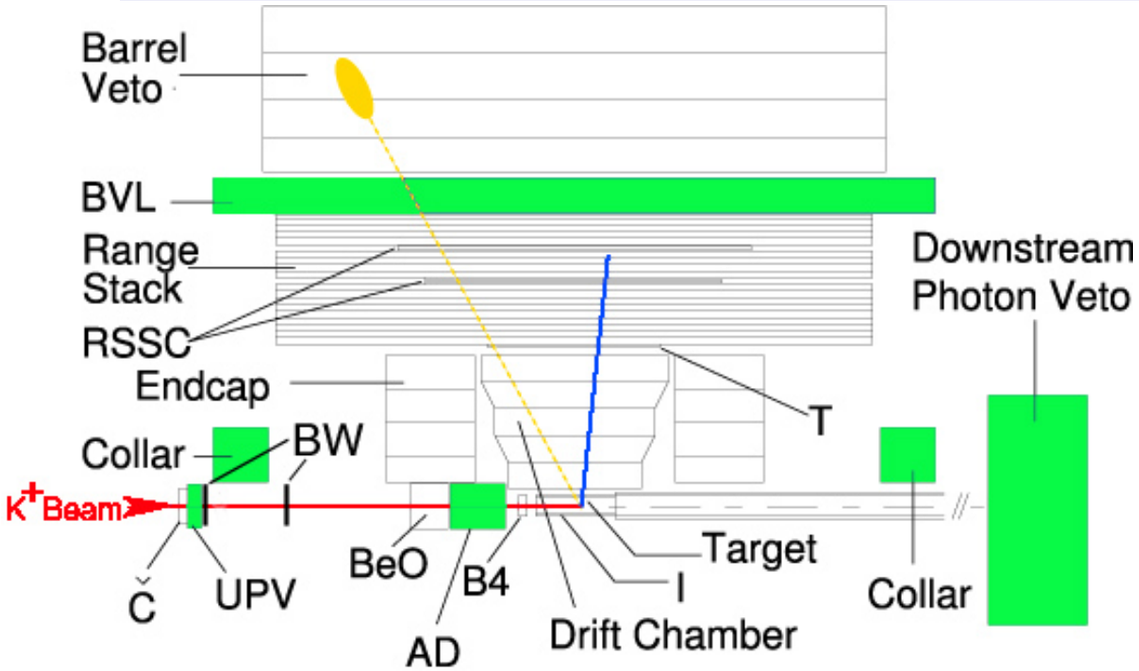


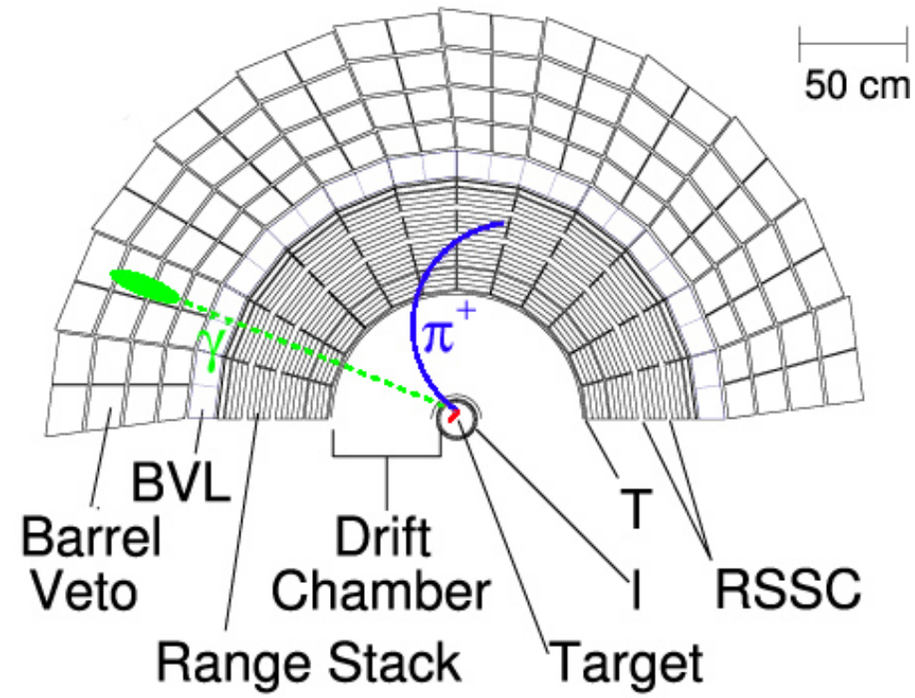
"~~Lions~~ $\gamma's$, and ~~Tigers~~ $\gamma's$, and ~~Bears~~ $\gamma's$! Oh, my!"

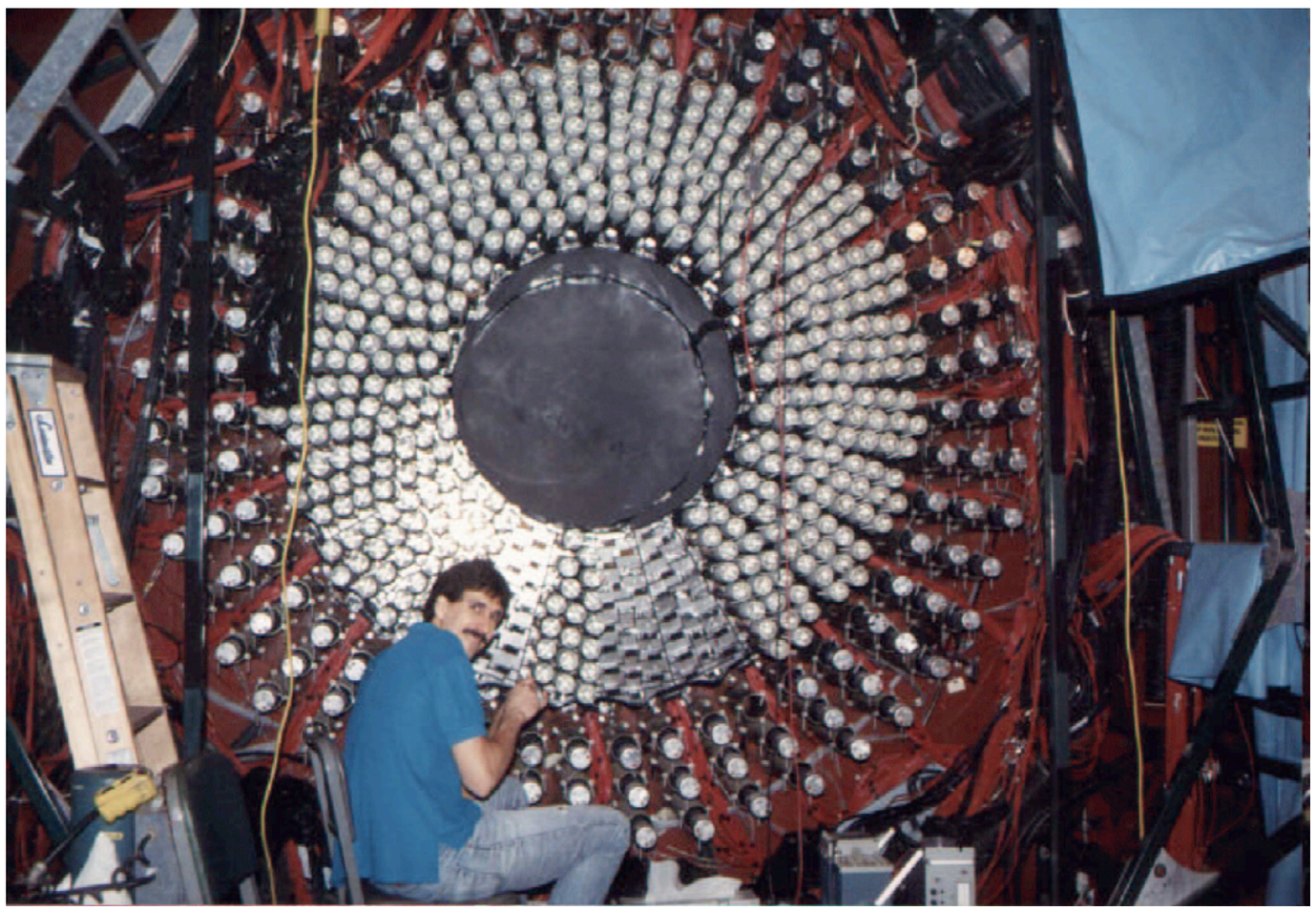
~~Dorothy~~ Benji

- E949 is one BIG Photon detector!

Detecting the γ's

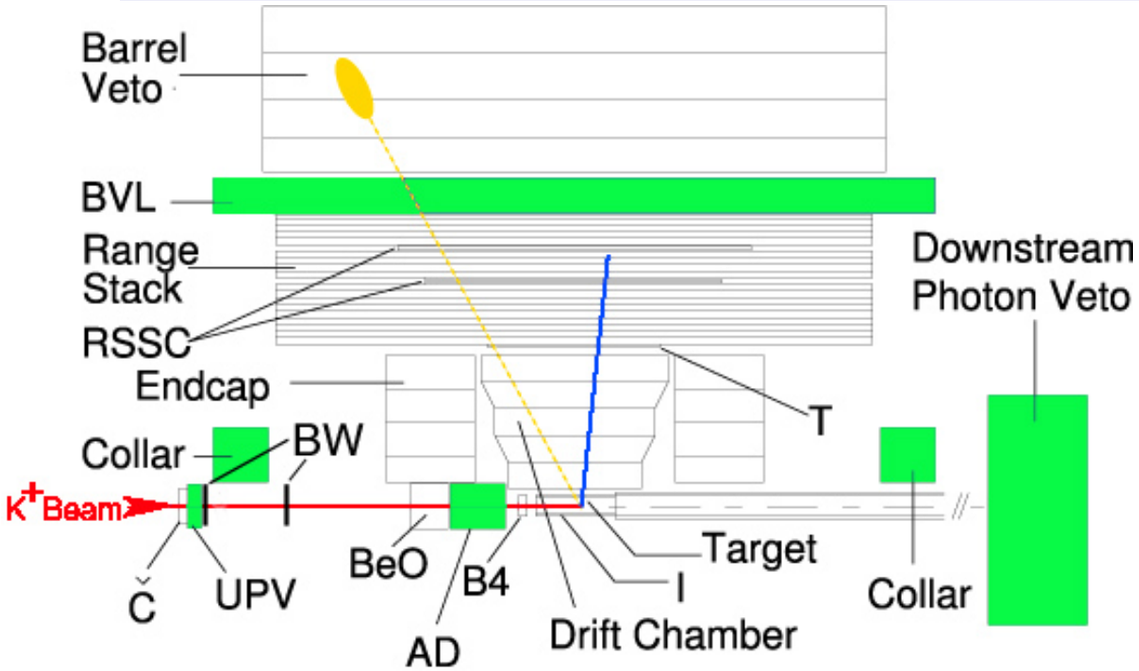


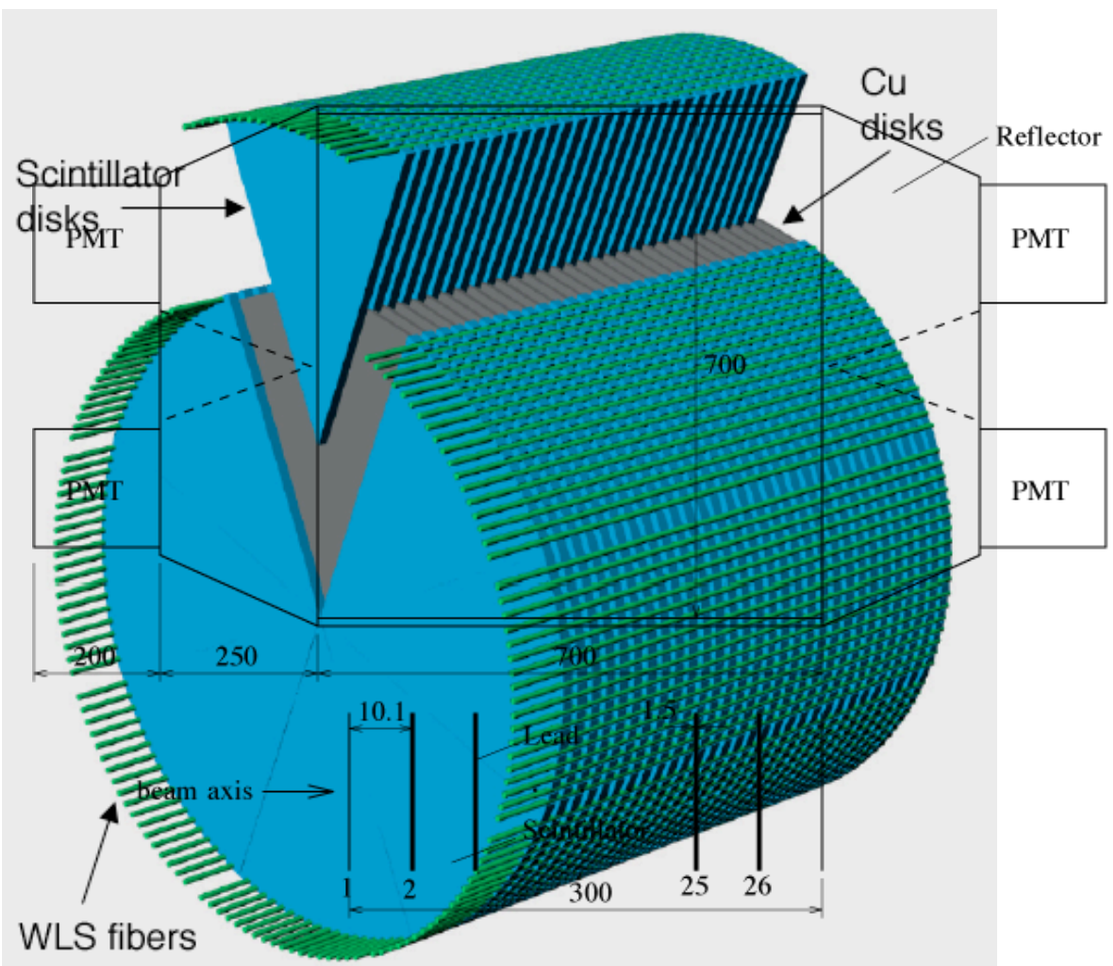




- Barrel Veto (BV)
  - Pb-scintillator
  - 14.3 rad. lengths
- BV-Liner (BVL)
  - Newer BV layer
  - Larger solid angle
  - 2.3 rad. lengths
- Range Stack
  - 0.8 rad. lengths
- Target
  - 0.2 rad. lengths
  - $\sim$ 6 rad. lengths in $+z$

Detecting the γ's





- End Caps (EC)

  CsI crystals

  13.5 rad. lengths

- Collars

  9 rad. lengths

- Active Degrader (AD)

  Detects upstream traveling γ's

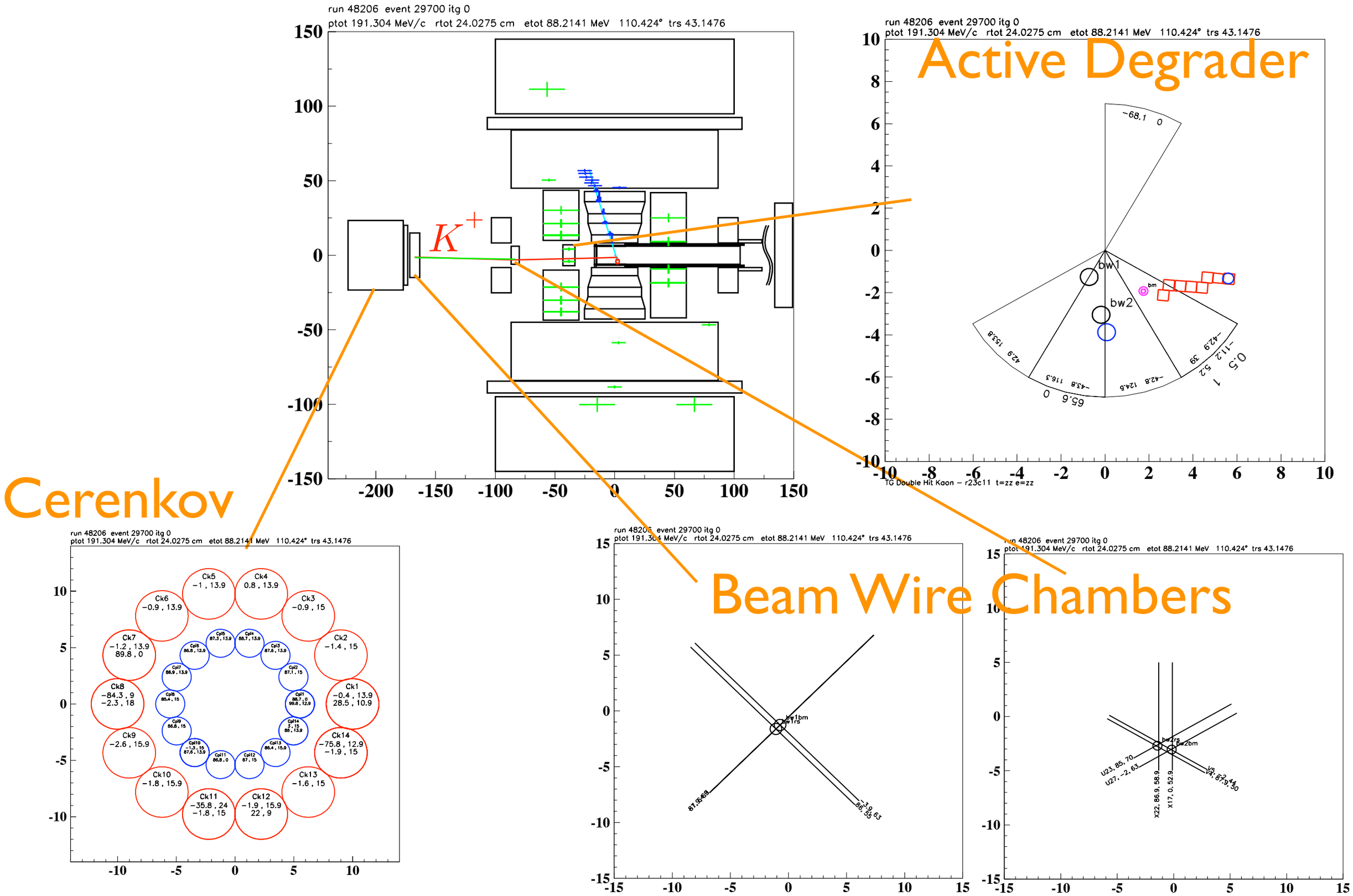
  $\sim$ 6 rad. lengths

- Downstream Photon Veto

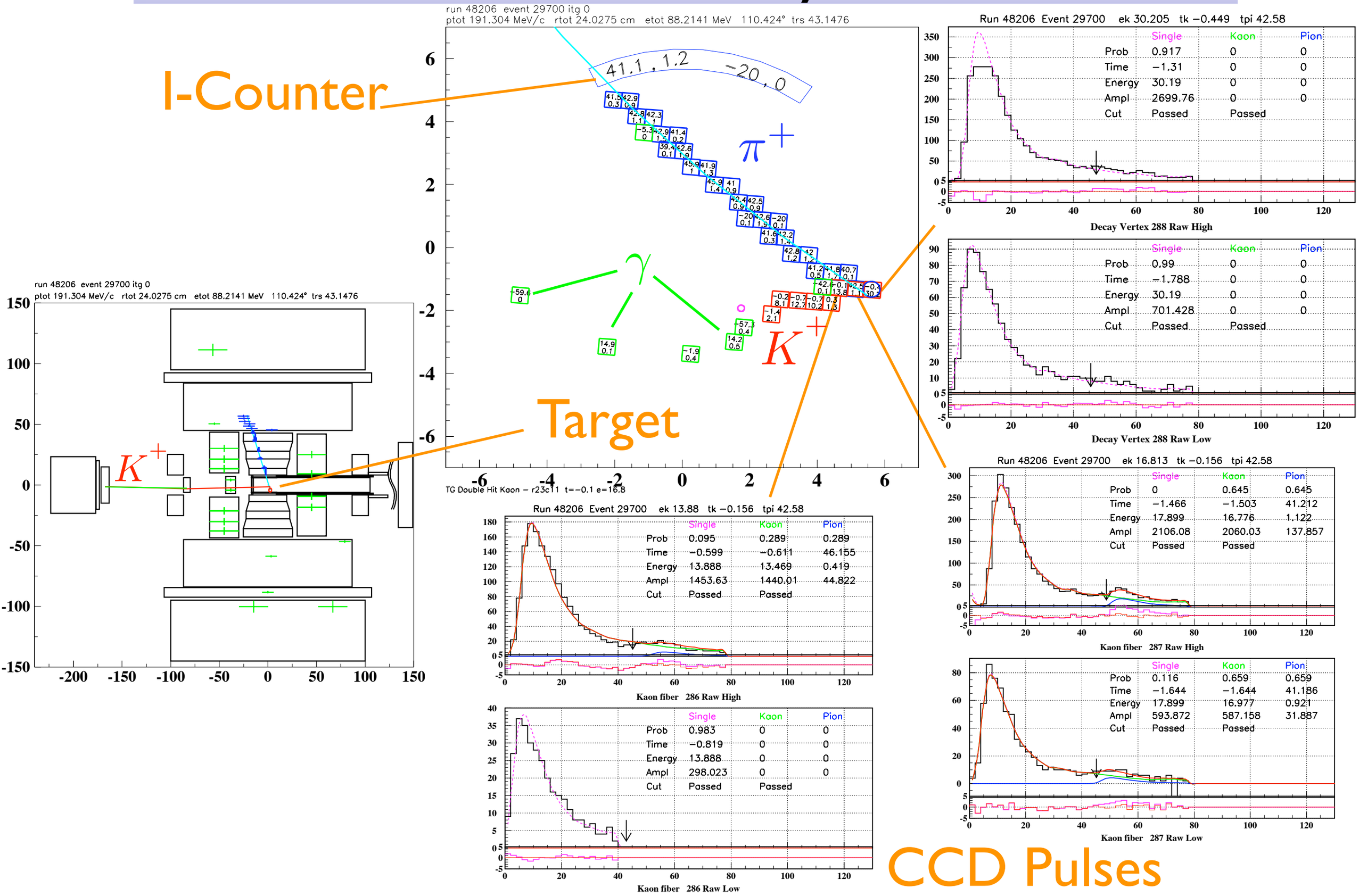
  $\sim$ 7 rad. lengths

  Detects downstream traveling γ's

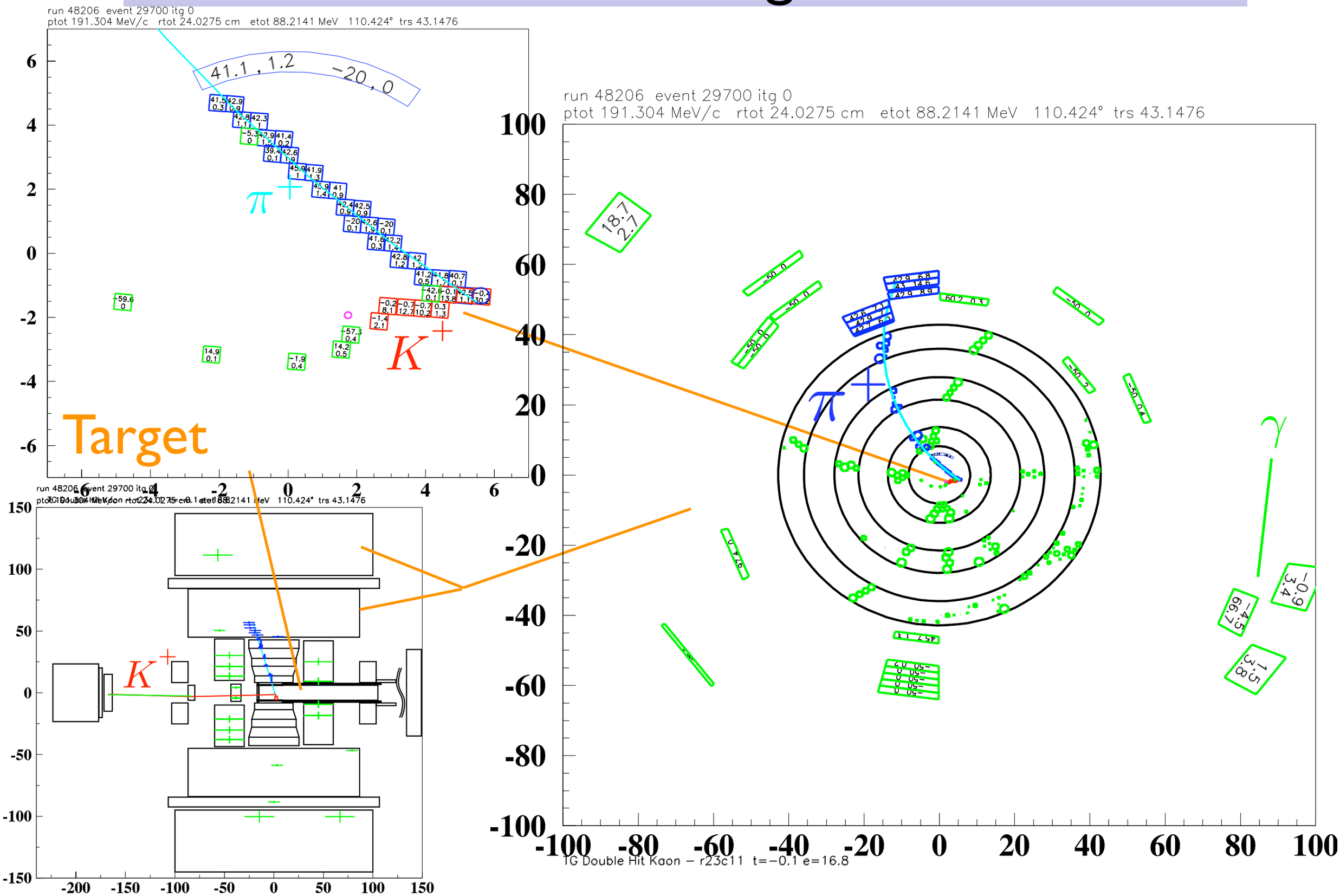
Beam Detectors



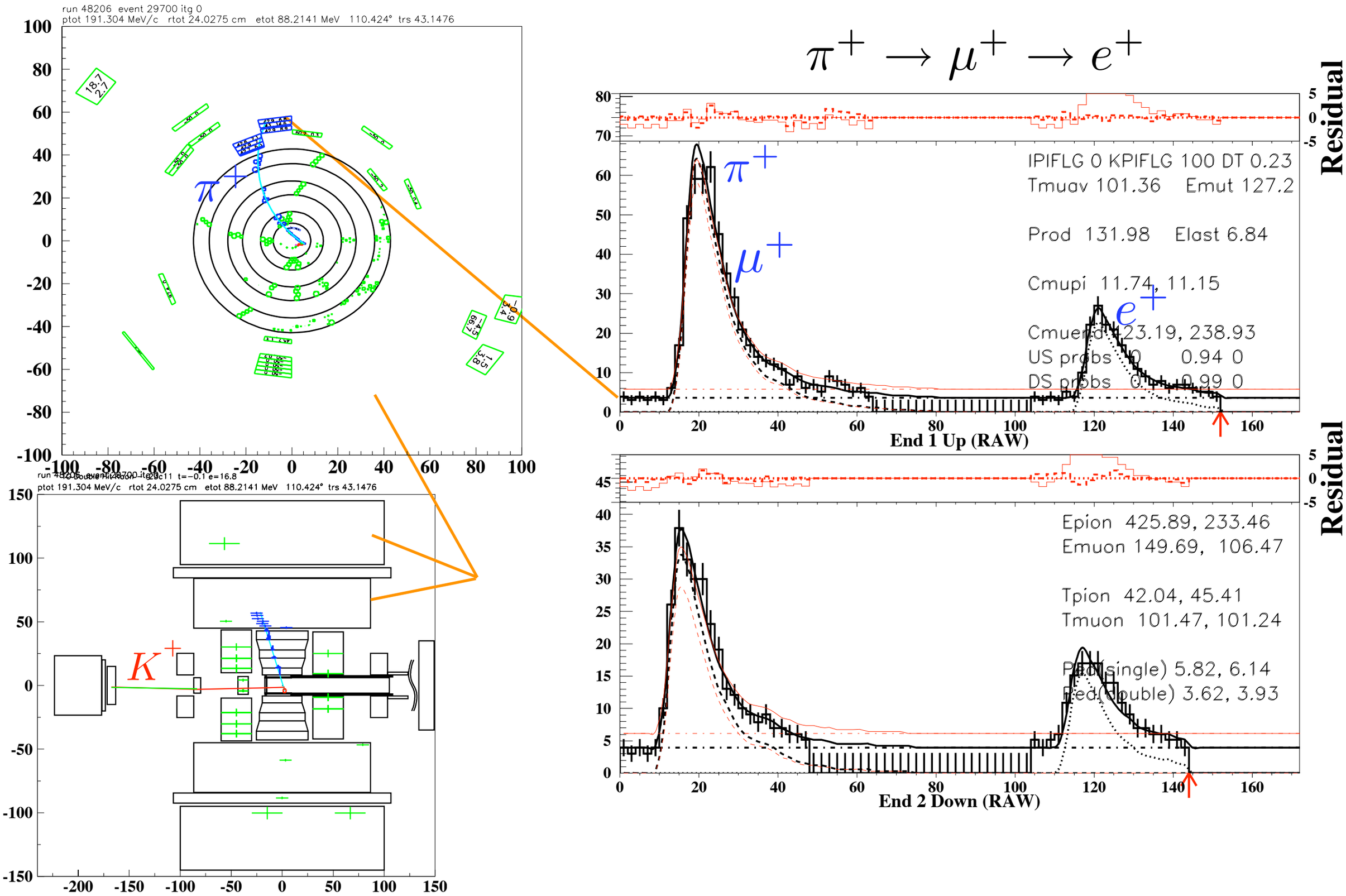
The Decay


I-Counter
Target
CCD Pulses
run 48206 event 29700 itg 0
ptot 191.304 MeV/c rtot 24.0275 cm etot 88.2141 MeV 110.424° trs 43.1476
TG Double Hit Kaon – r23c11 t=–0.1 e=16.8
Run 48206 Event 29700 ek 30.205 tk –0.449 tpi 42.58
Decay Vertex 288 Raw High
Decay Vertex 288 Raw Low
Run 48206 Event 29700 ek 16.813 tk –0.156 tpi 42.58
Kaon fiber 287 Raw High
Kaon fiber 287 Raw Low
Run 48206 Event 29700 ek 13.88 tk –0.156 tpi 42.58
Kaon fiber 286 Raw High
Kaon fiber 286 Raw Low
Single Kaon Pion
Prob 0.917 0 0
Time –1.31 0 0
Energy 30.19 0 0
Ampl 2699.76 0 0
Cut Passed Passed
Prob 0.99 0 0
Time –1.788 0 0
Energy 30.19 0 0
Ampl 701.428 0 0
Cut Passed Passed
Prob 0 0.645 0.645
Time –1.466 –1.503 41.212
Energy 17.899 16.776 1.122
Ampl 2106.08 2060.03 137.857
Cut Passed Passed
Prob 0.116 0.659 0.659
Time –1.644 –1.644 41.186
Energy 17.899 16.977 0.921
Ampl 593.872 587.158 31.887
Cut Passed Passed
Prob 0.095 0.289 0.289
Time –0.599 –0.611 46.155
Energy 13.888 13.469 0.419
Ampl 1453.63 1440.01 44.822
Cut Passed Passed
Prob 0.983 0 0
Time –0.819 0 0
Energy 13.888 0 0
Ampl 298.023 0 0
Cut Passed Passed
π^+
γ
K^+
K^+

Tracking


run 48206 event 29700 itg 0
ptot 191.304 MeV/c rtot 24.0275 cm etot 88.2141 MeV 110.424° trs 43.1476
Target
TG Double Hit Kaon – r23c11 t=−0.1 e=16.8

Tracking


run 48206 event 29700 itg 0
ptot 191.304 MeV/c rtot 24.0275 cm etot 88.2141 MeV 110.424° trs 43.1476
π^+
K^+
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$
π^+
μ^+
e^+
IPIFLG 0 KPIFLG 100 DT 0.23
Tmuav 101.36 Emut 127.2
Prod 131.98 Elast 6.84
Cmupi 11.74, 11.15
Cmuend 123.19, 238.93
US probs 0 0.94 0
DS probs 0 0.99 0
End 1 Up (RAW)
Residual
Epion 425.89, 233.46
Emuon 149.69, 106.47
Tpion 42.04, 45.41
Tmuon 101.47, 101.24
Pedi(single) 5.82, 6.14
Pedi(double) 3.62, 3.93
End 2 Down (RAW)
Residual

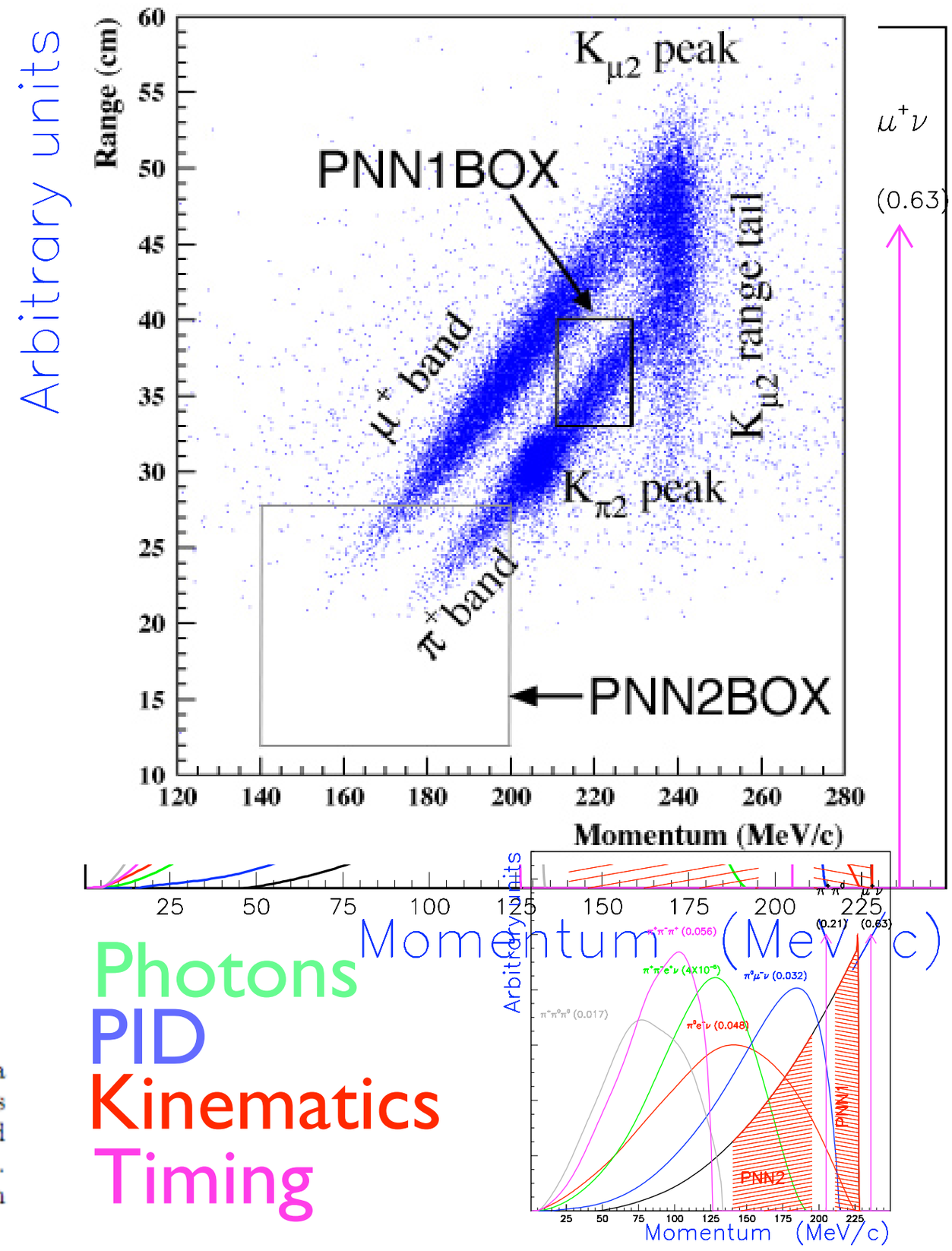
Analysis Strategy

- *A priori* background identification.
- "Blind Analysis" never inspect signal region until backgrounds are proven.
- Avoid bias by optimizing cuts on 1/3 sample and measuring backgrounds with 2/3 sample.
- Suppress each background with (at least) 2 independent cuts.
- Use data whenever possible.
- Loosen and tighten cut to compare to predicted rates.

Possible PNN1 Backgrounds from Decays

Background	Branching Ratio	Track Kin.	Extra Energy	DC	Particle ID	Photons
$K^+ \to \mu^+\nu$						
$K^+ \to \pi^+\pi^0$						
$K^+ \to \mu^+\nu\gamma$						
$K^+ \to \mu^+\nu\nu\bar{\nu}$						
$K^+n \to K^0p$	0.000028		✓	✓		
$K_L^0 \to \pi^+\mu^-\bar{\nu}$						
$K_L^0 \to \pi^+e^-\bar{\nu}$						

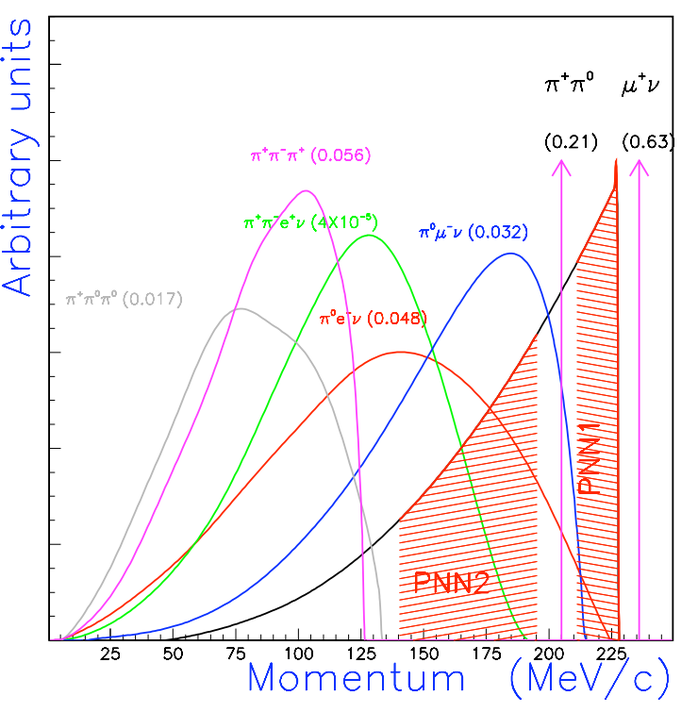
Table 3.1: Background processes with their Branching Ratios [5]. ✓ denotes a quality which distinguishes the process from the signal. X (X*) identifies the process as kinematically forbidden in PNN2 signal region (, but very close). The reported branching ratio of $K^+n \to K^0p$ is the K_L production rate as found in [37]. Kin. = Kinematics, DC = Delayed Coincidence, ID = Identification, $\checkmark^n$ = n photons in product.



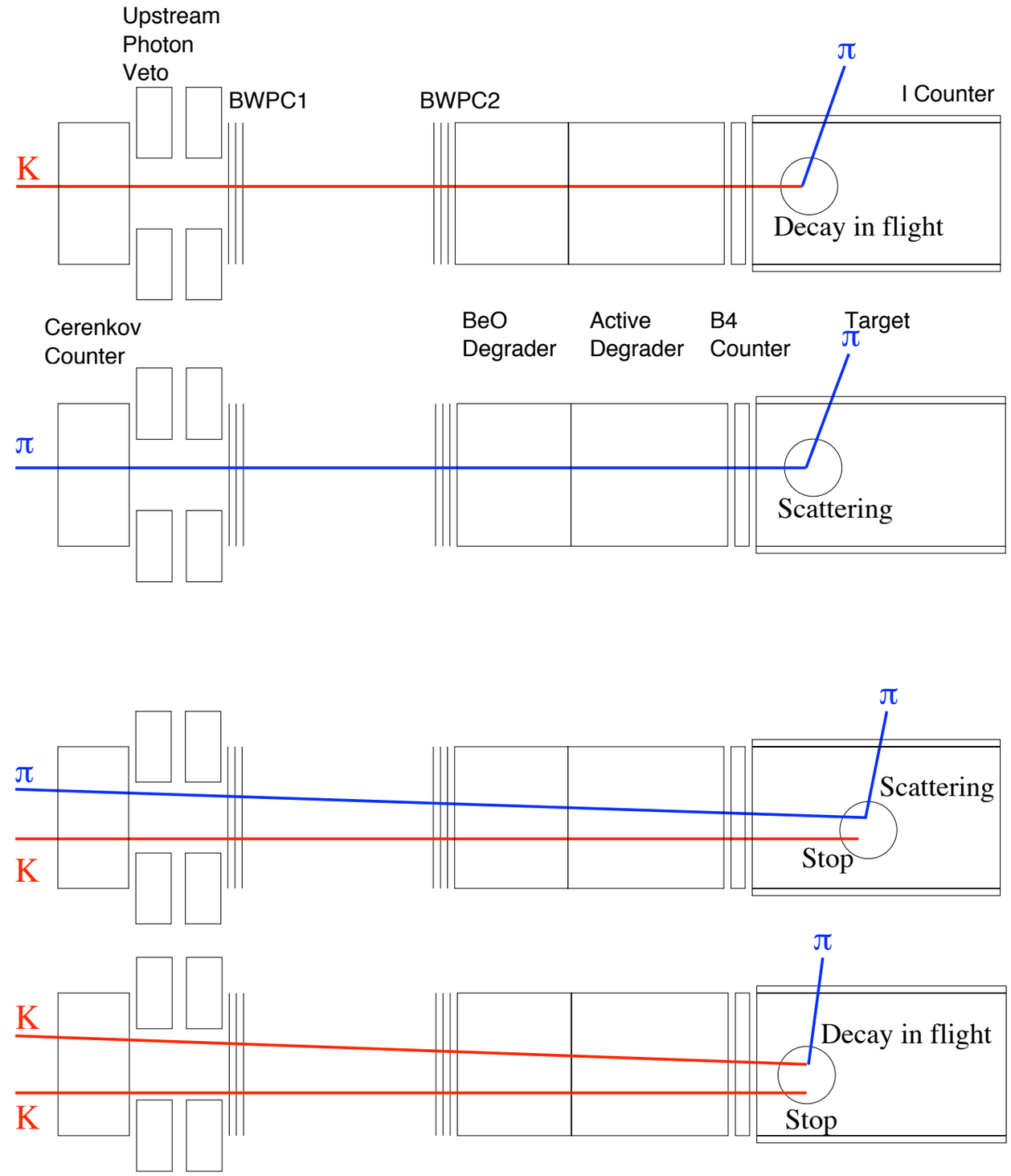
Possible PNN1 Backgrounds

Background	Branching Ratio	Track Kin.	Extra Energy	DC	Particle ID Track	Particle ID Beam	Photons Fid.	Photons Beam
π-Beam								
K-DIF								
KK-Beam								
Kπ-Beam								
Charged-track scatter in Target								
K								
Charged-track scatter in Range Stack								
$K^+ \to \mu^+\nu$								

Table 3.2: Background processes with their Branching Ratios [5]. ✓ denotes a quality which distinguishes the process from the signal. X identifies the process as kinematically forbidden in PNN2 signal region. DIF = Delay in Flight, Kin. = Kinematics, DC = Delayed Coincidence, ID = Identification, Fid. = Fiducial region photon detection, ✓* = depends on which K^+ decay, ✓^{P} = distinguished by momentum



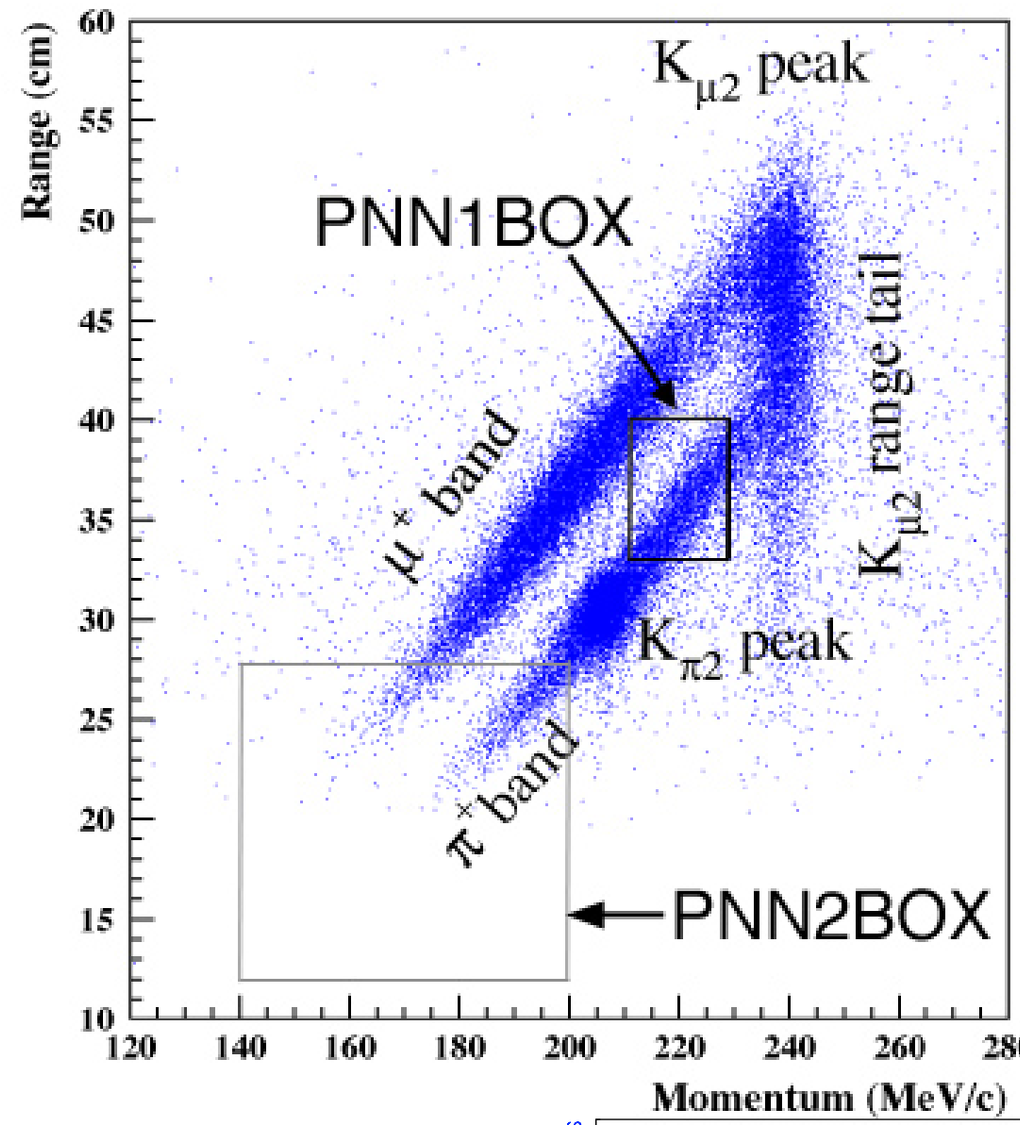
Timing
PID
Photons
Kinematics



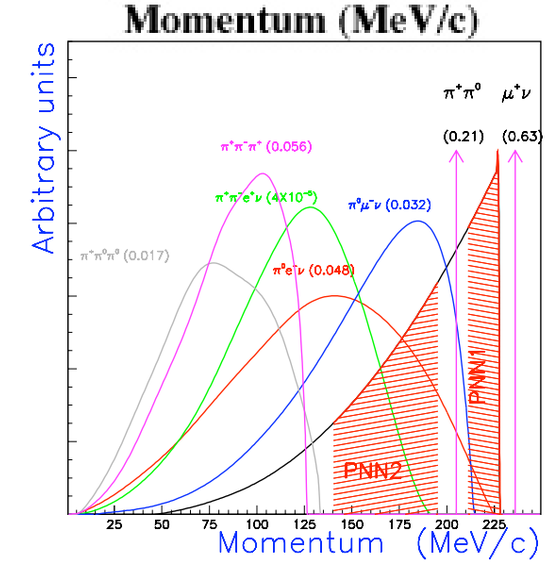
Possible PNN2 Backgrounds from Decays

Background	Branching Ratio	Track Kin.	Extra Energy	DC	Particle ID	Photons
$K^+ \to \mu^+\nu\gamma$	0.0062					
$K^+ \to \pi^+\pi^-e^+\nu$	0.0000409					
$K^+ \to \pi^+\pi^-\mu^+\nu$						
$K^+ \to \mu^+\nu\nu\bar{\nu}$	< 0.000006					
$K^+ \to$						
$K^+n \to K^0p$	0.000028		✓	✓		
$K_L^0 \to \pi^+\mu^-\bar{\nu}$						
$K_L^0 \to \pi^+e^-\bar{\nu}$						

Table 3.1: Background processes with their Branching Ratios [5]. ✓ denotes a quality which distinguishes the process from the signal. X (X*) identifies the process as kinematically forbidden in PNN2 signal region (, but very close). The reported branching ratio of $K^+n \to K^0p$ is the K_L production rate as found in [37]. Kin. = Kinematics, DC = Delayed Coincidence, ID = Identification, $\checkmark^n$ = n photons in product.



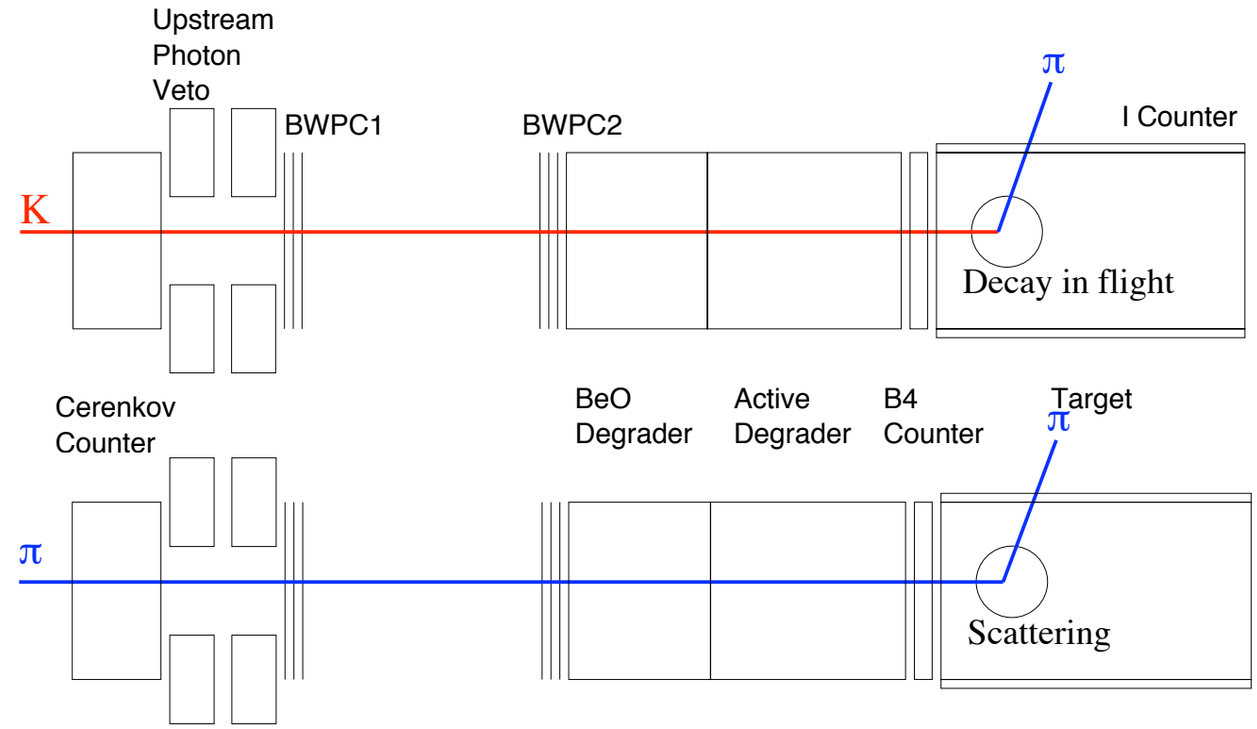
Photons
Kinematics
PID
Timing

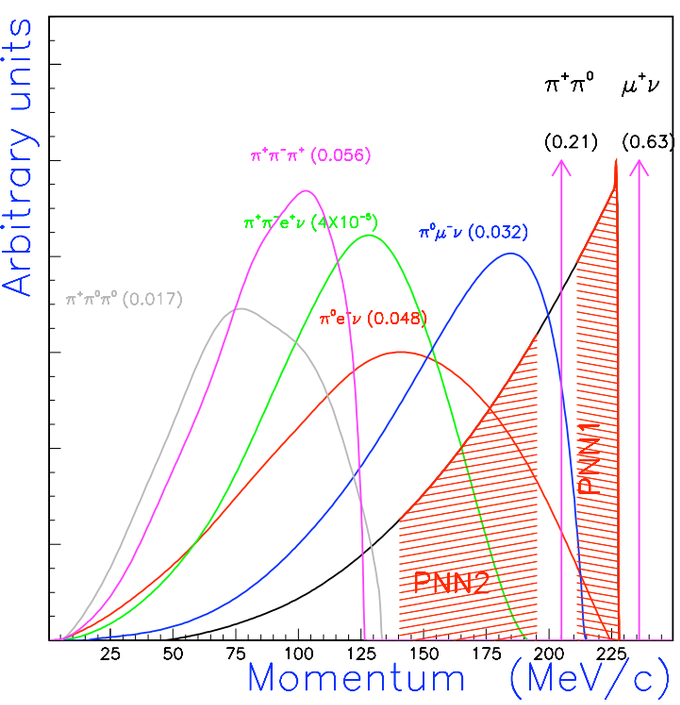


Possible PNN2 Backgrounds

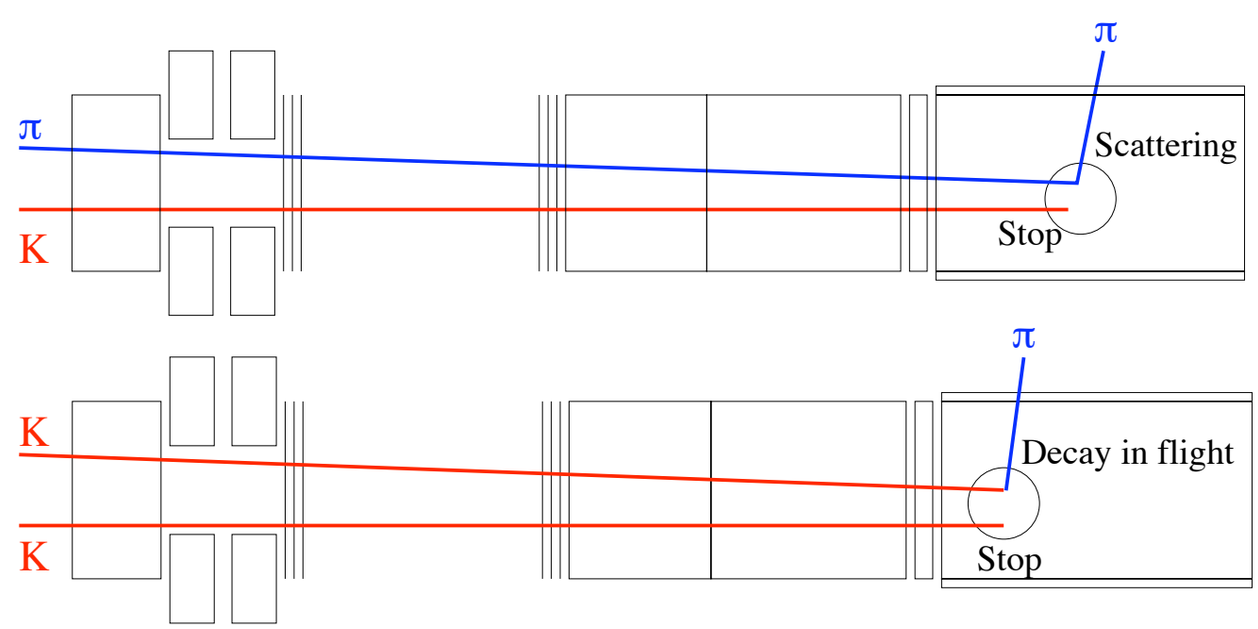
Background	Branching Ratio	Track Kin.	Extra Energy	DC	Particle ID Track	Particle ID Beam	Photons Fid.	Photons Beam
π-Beam								
K-DIF								
KK-Beam	-							
Kπ-Beam	-							
Charged-track scatter in Target								
$K^+ \to \pi^+\pi^0$	0.2092		✓					
$K^+ \to \pi^+\pi^0\gamma$								
Charged-track scatter in Range Stack								
$K^+ \to \pi^+\pi^0$								
$K^+ \to \pi^+\pi^0\gamma$								

Table 3.2: Background processes with their Branching Ratios [5]. ✓ denotes a quality which distinguishes the process from the signal. X identifies the process as kinematically forbidden in PNN2 signal region. DIF = Delay in Flight, Kin. = Kinematics, DC = Delayed Coincidence, ID = Identification, Fid. = Fiducial region photon detection, $\checkmark^*$ = depends on which K^+ decay, $\checkmark^P$ = distinguished by momentum

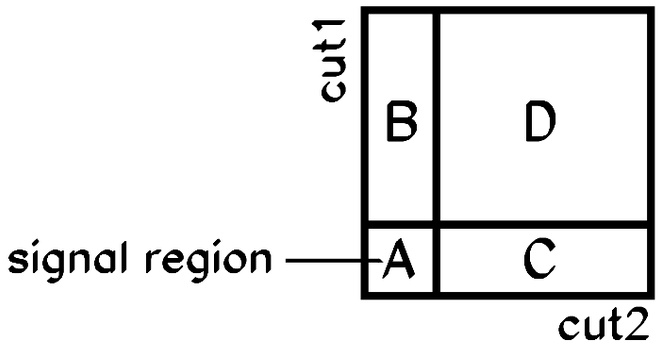




Timing
PID
Photons
Kinematics



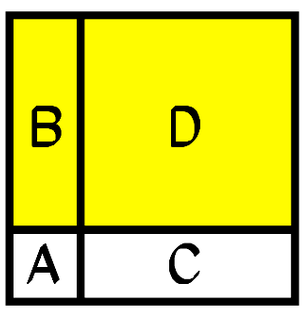
Bifurcation Method



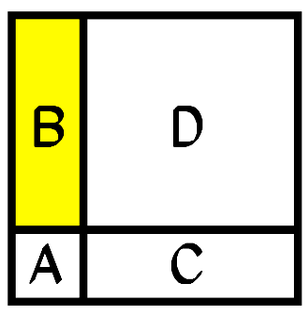
if cut1,cut2
uncorrelated,

$A/B = C/D$

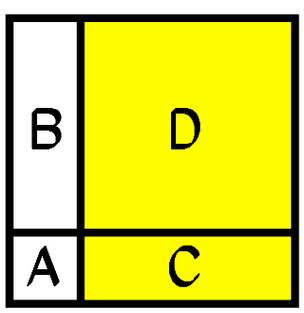
$A = BC/D$



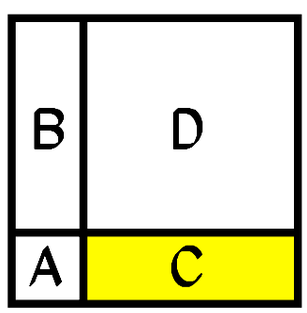
invert cut1
B+D events



apply cut2
B events



invert cut2
C+D events

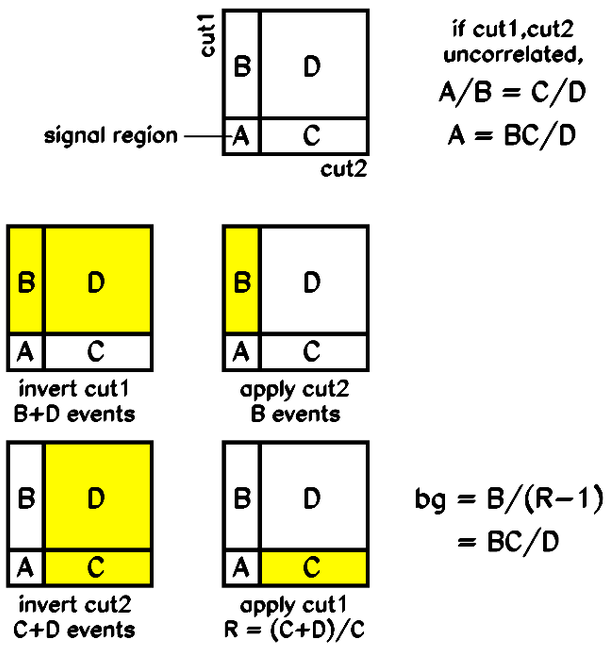


apply cut1
$R = (C+D)/C$

$bg = B/(R-1)$
$= BC/D$

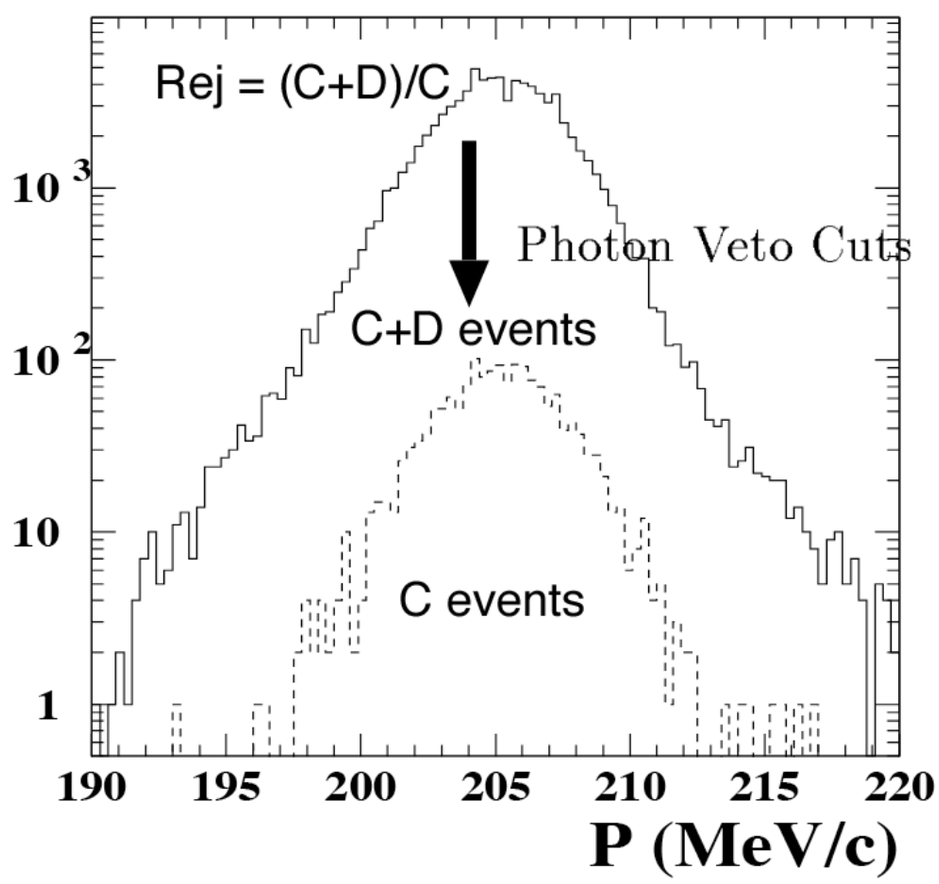
- Signal Region (A) always blinded.
  until the end.
- Cuts must be uncorrelated.
  such as PID & Kinematics

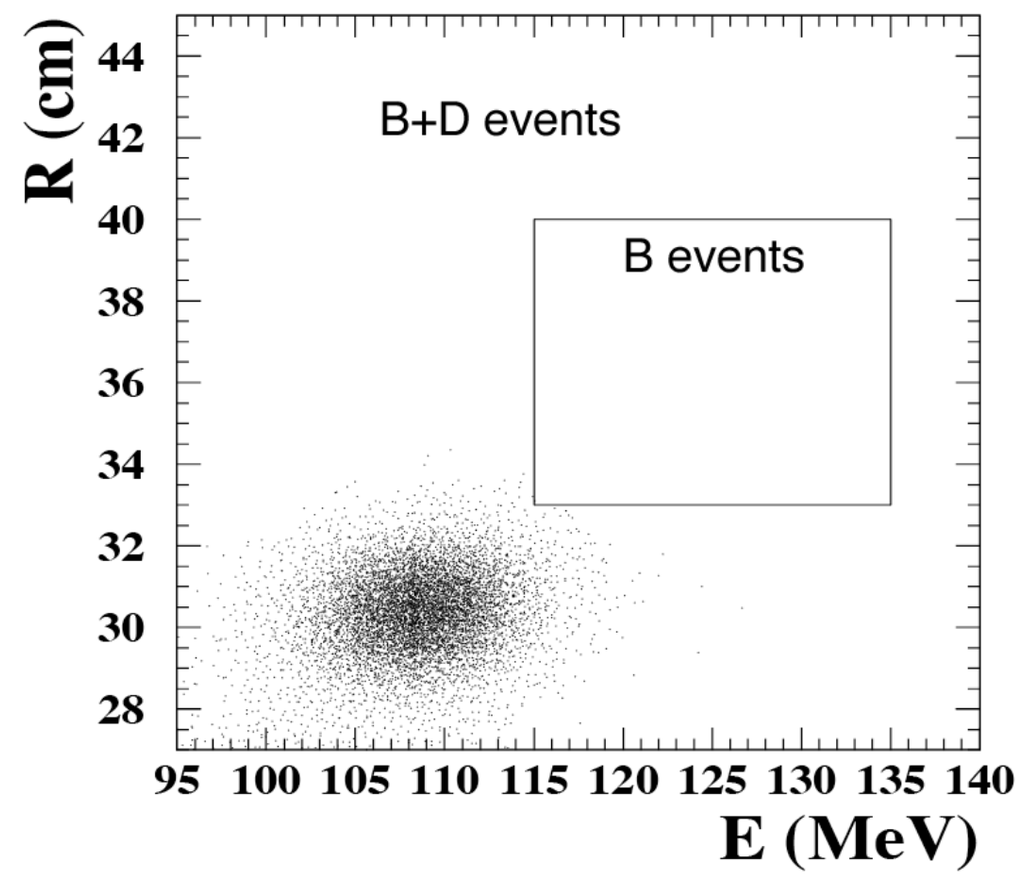
Bifurcation Method



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

- **Left:** Select events by $\overline{kinematics}$ (C+D).
  - Apply Photon Veto (C).
  - Measure $Rejection = \frac{C+D}{C}$.
- **Right:** Select events by $\overline{photon\ cuts}$ (B+D).
  - Apply Kinematics (B).
  - $Background = \frac{B}{R-1}$.





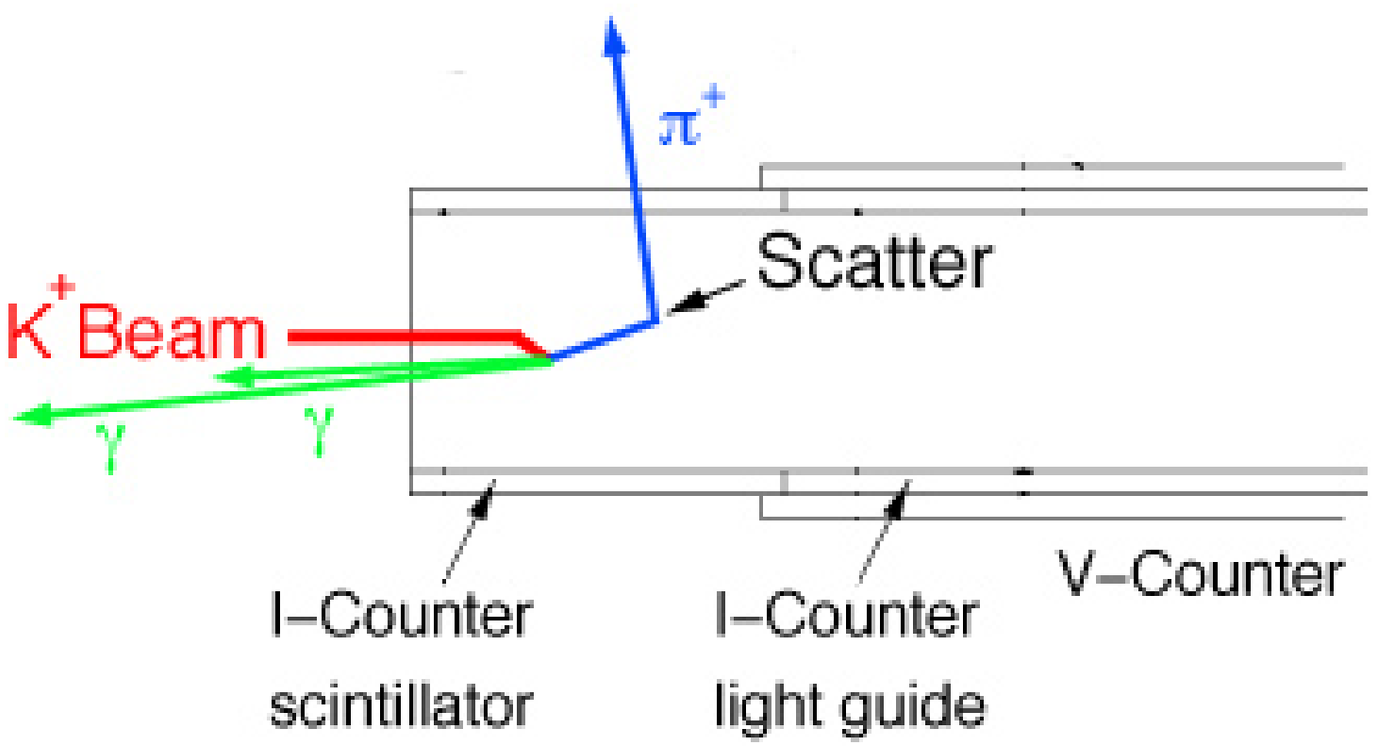
$K_{\pi 2}$ TG-Scatter

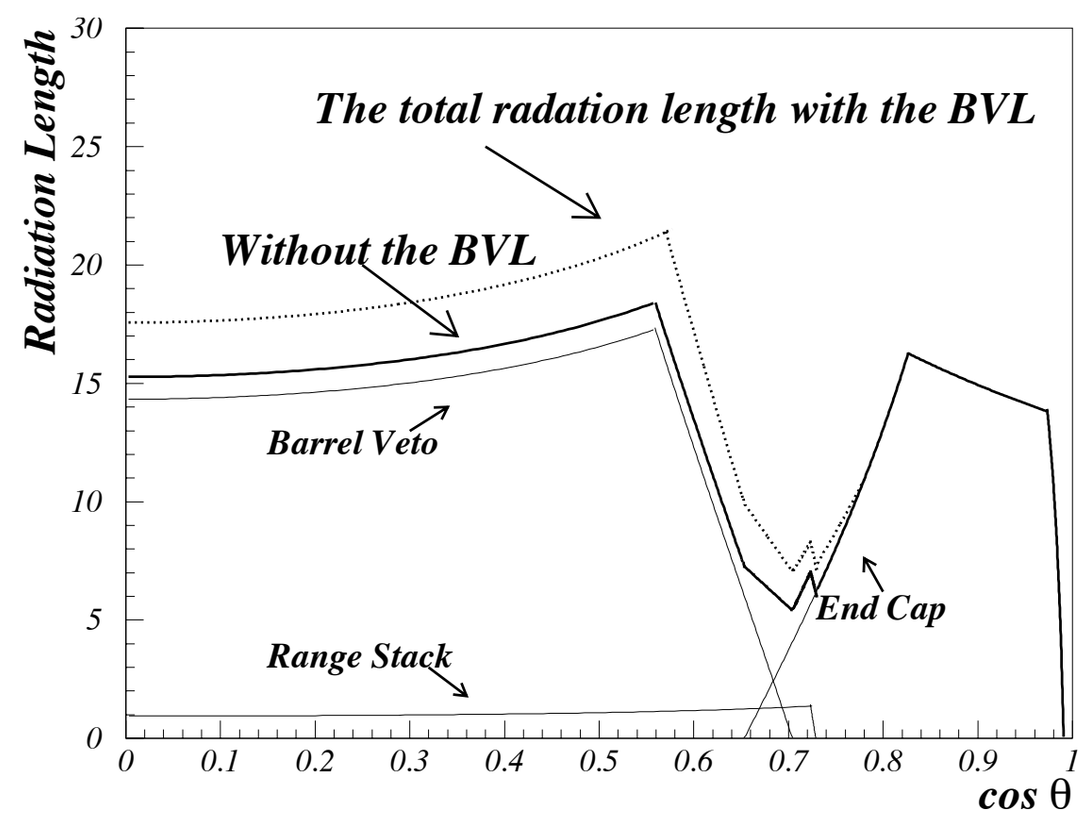
"Houston, we've had a problem."
James A. Lovell

- π^0 correlated to π^+ before scatter

  Not so after scatter.

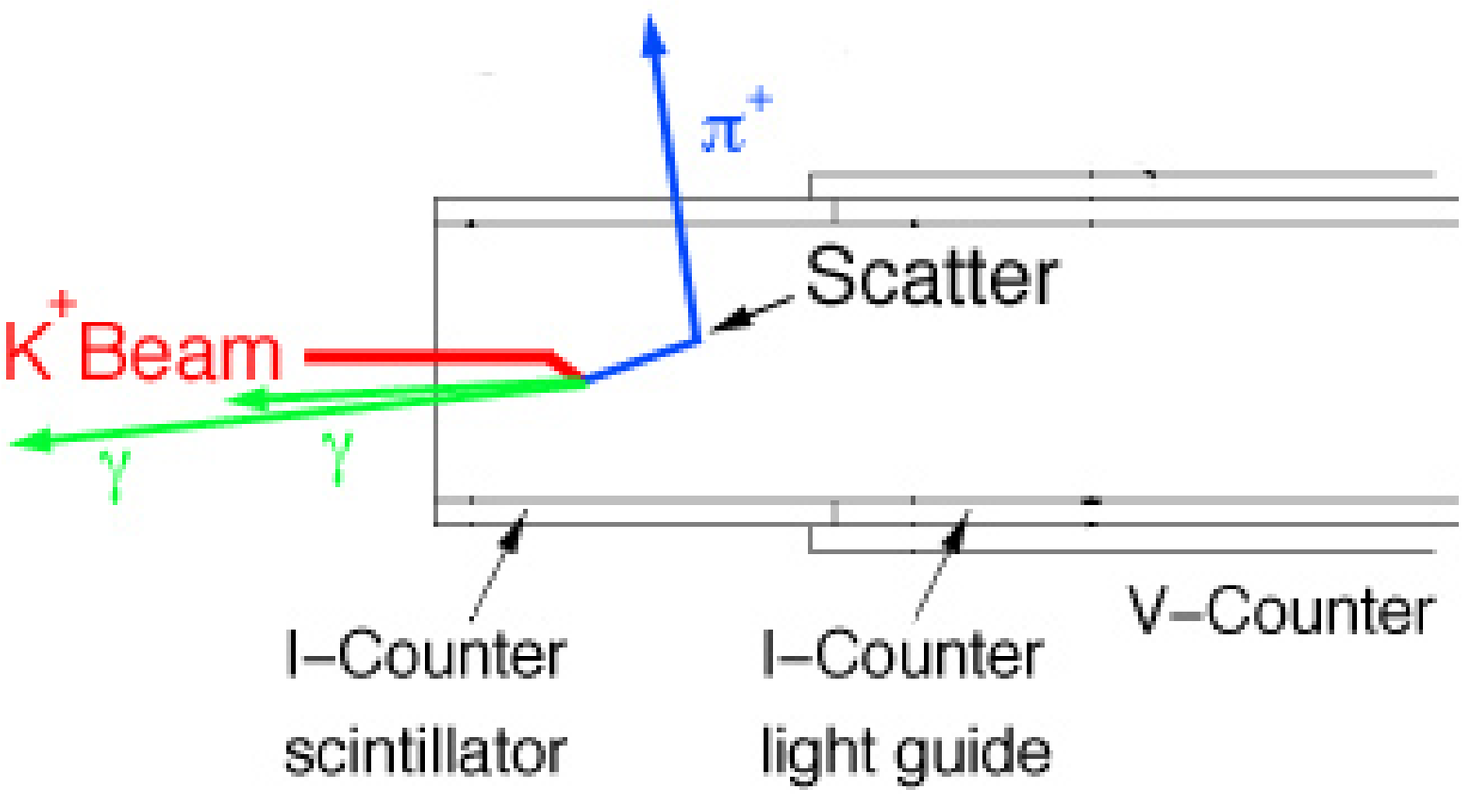
- γ's from π^0 directed toward weak photon coverage
- TG has no z resolution, so UTC/TG tracking matching not helpful.
- π^+ from $K_{\pi 2}$ @ 205 MeV/c may now be in PNN2 signal region.
- No longer able to 'tag' with kinematics to measure photon-veto rejection.

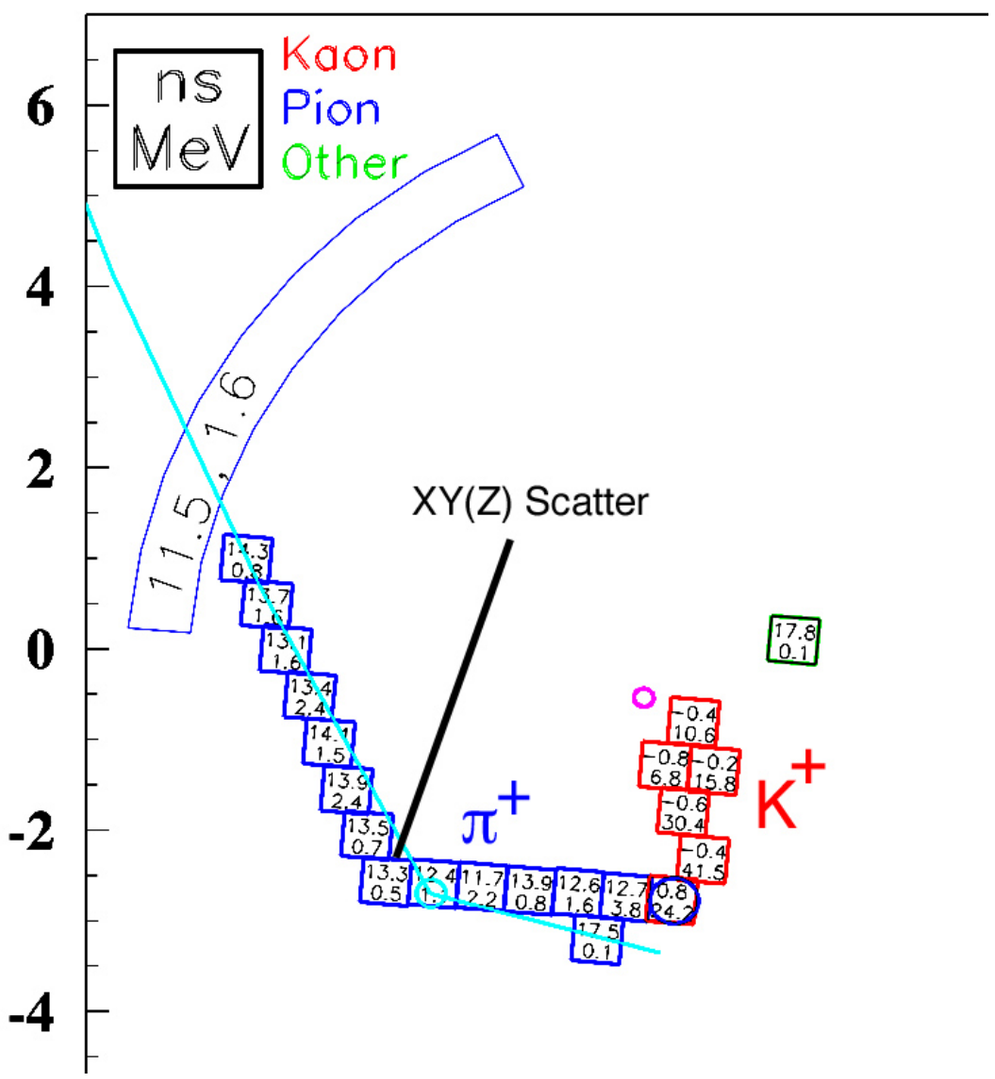




Mastering the $K_{\pi 2}$-scatter Background

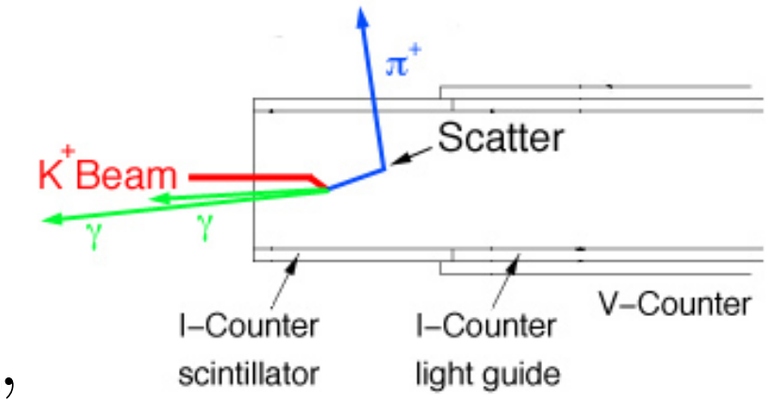
- Identify 'Kink' sample, $XY(Z)$ scatters, by observing pattern in π fibers.
- Use this sample for understanding rejection of photons along beam direction (z-axis).

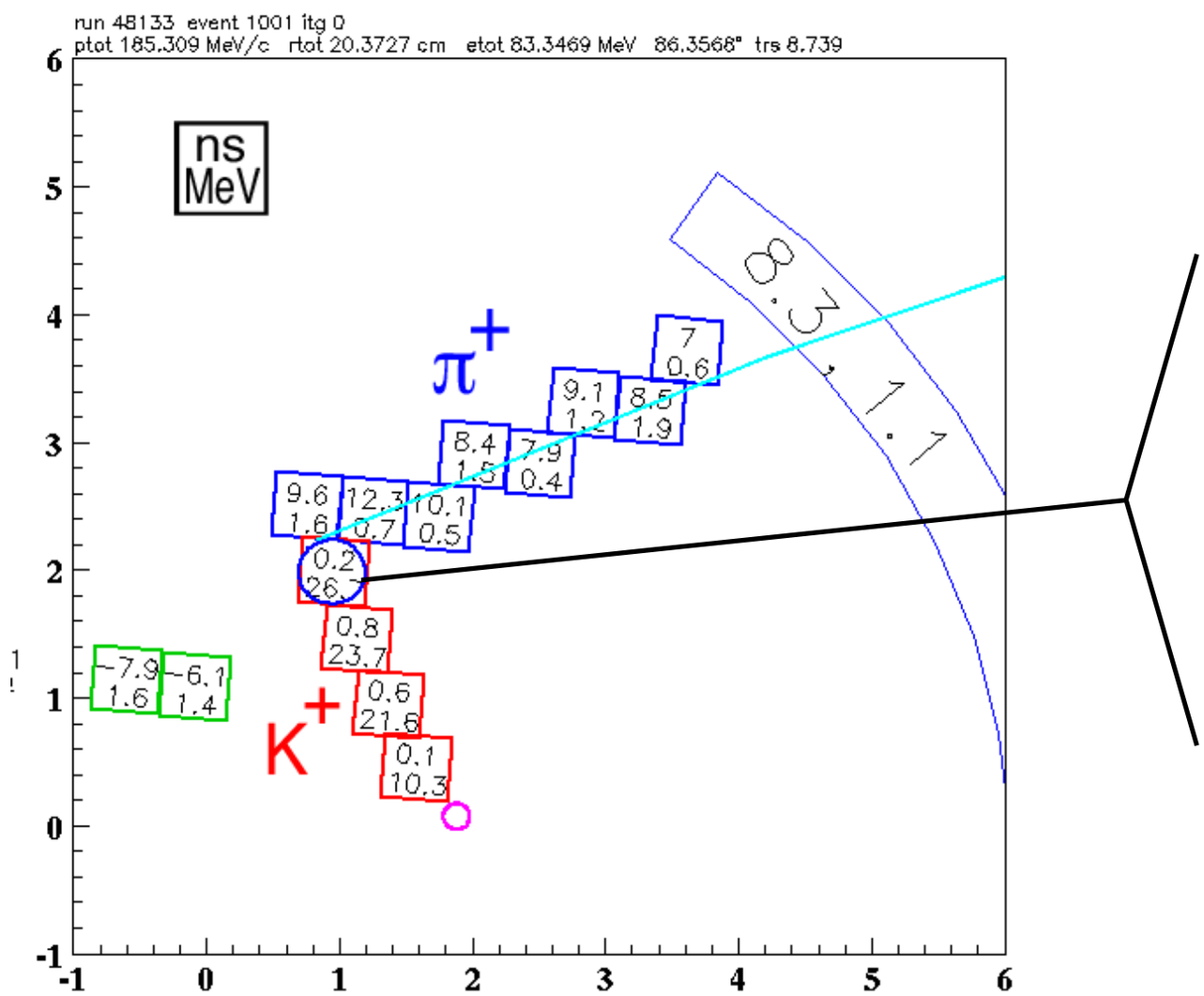


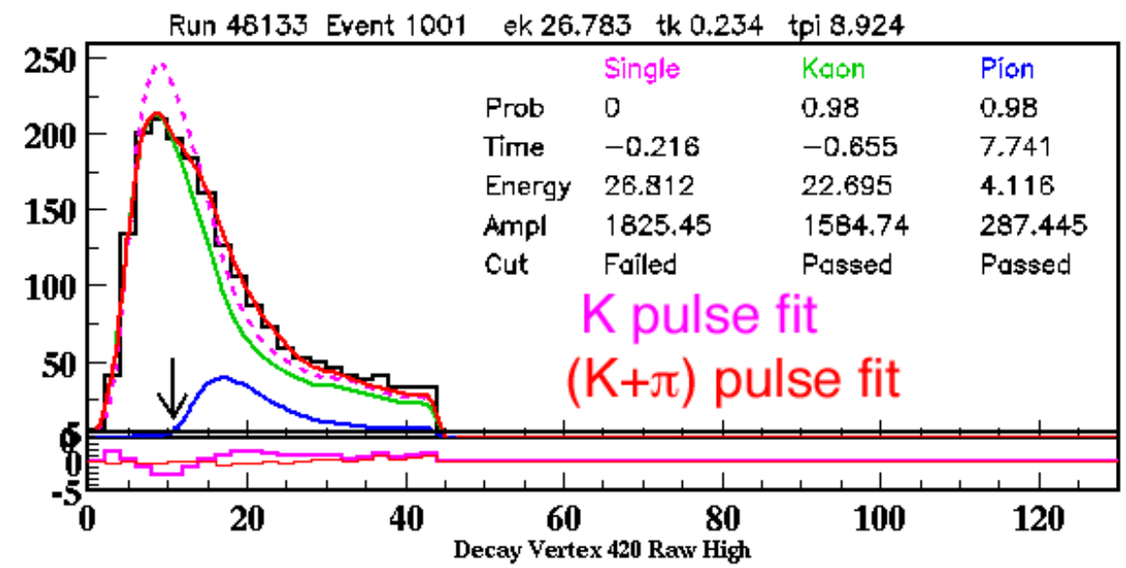


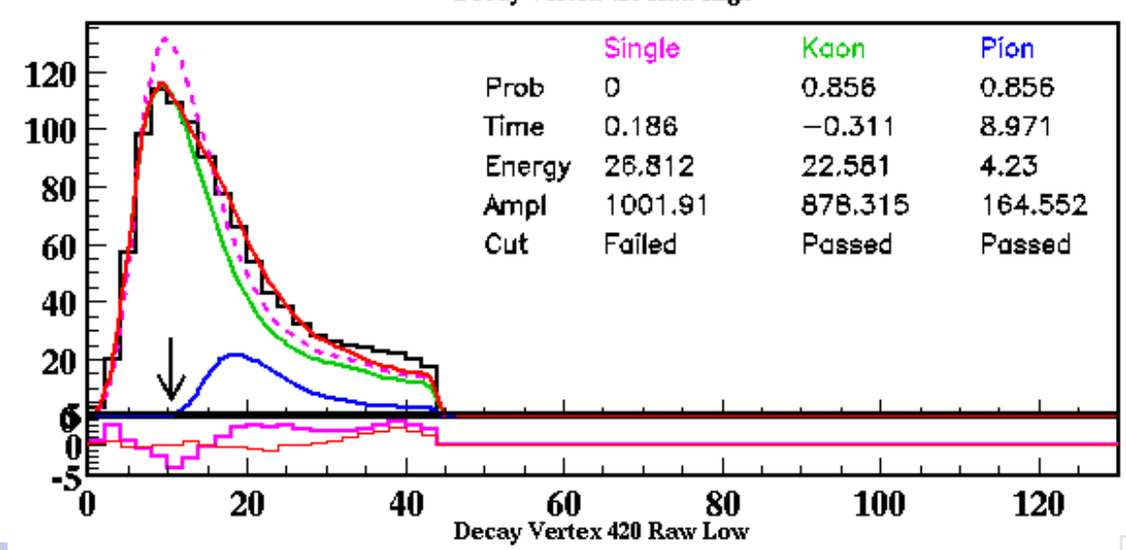
Mastering the $K_{\pi 2}$-scatter Background

- Identify excess 2nd pulse energy in K^+ fibers, "CCDPUL" ($> 1.25 MeV$).
- Identify events where the total K^+ energy in TG does not match the expected range in TG "B4EKZ".

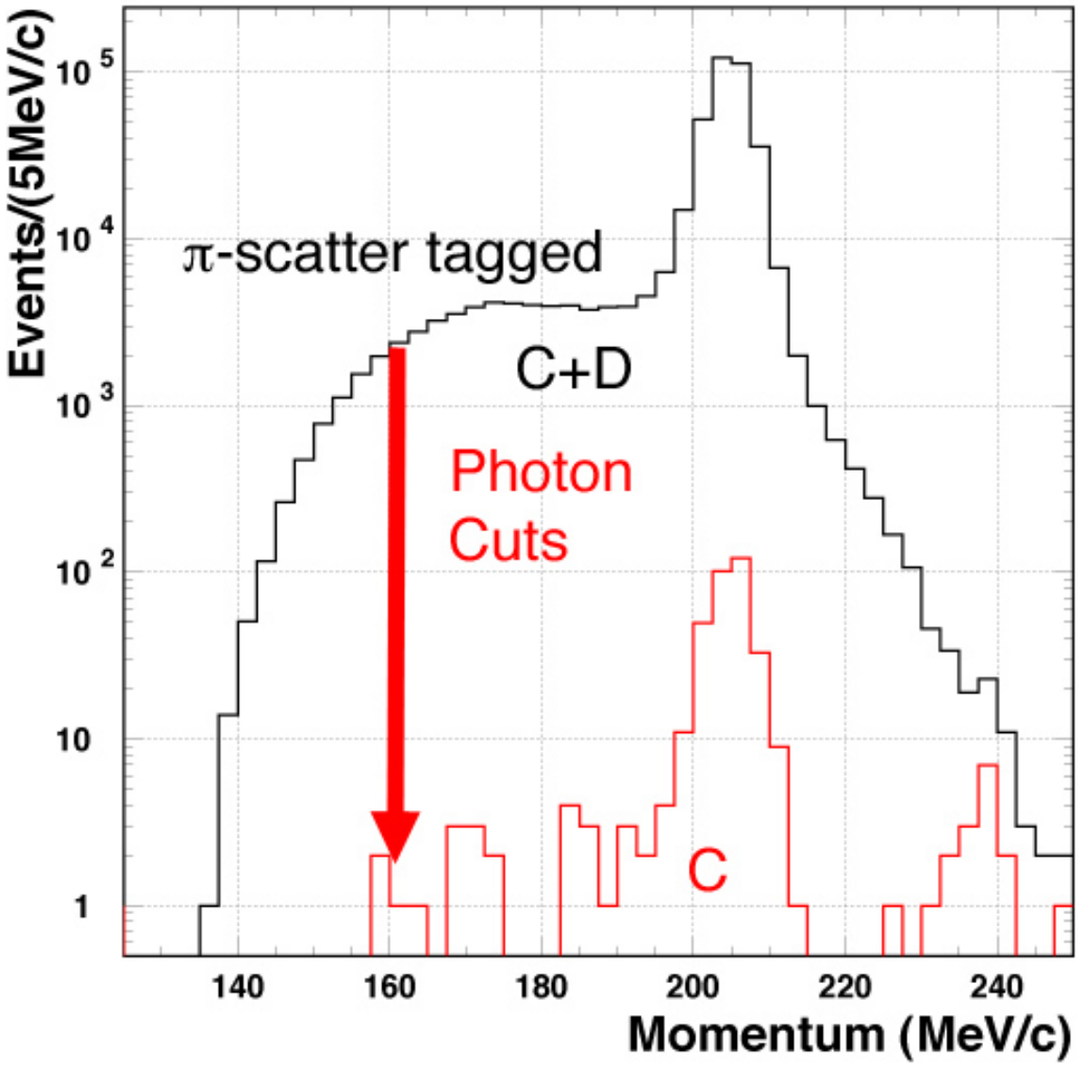


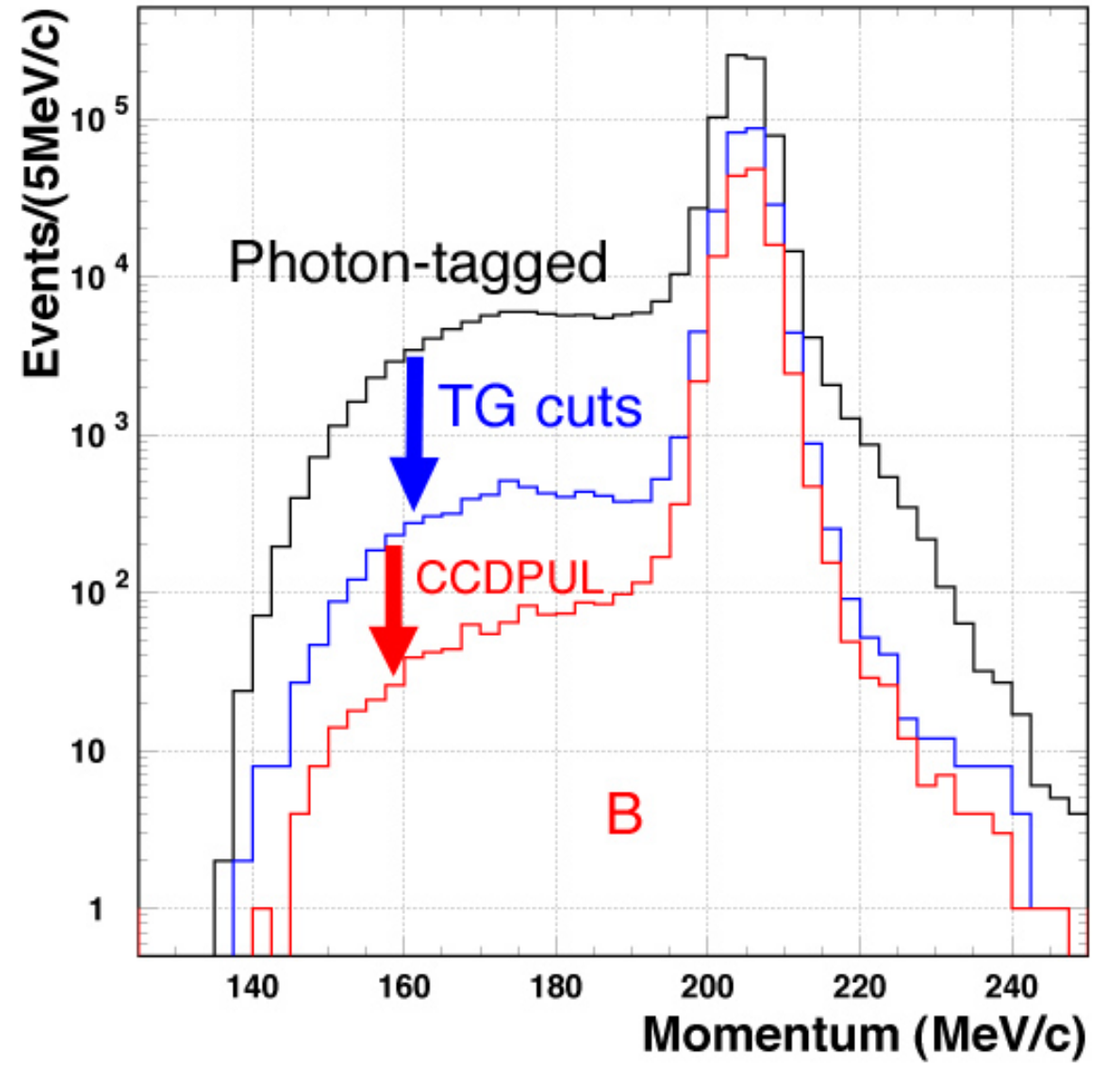




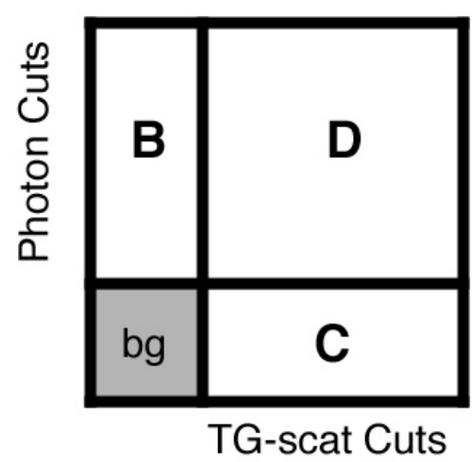


Measuring $K_{\pi 2}$ TG-Scatter Background





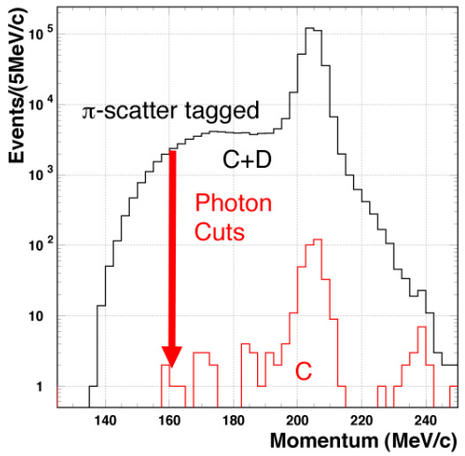
Measure Rejection of Photon Cuts

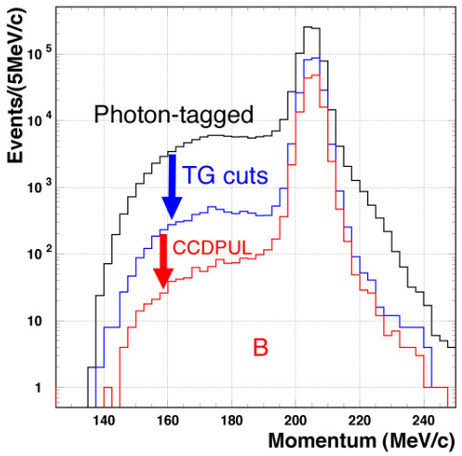


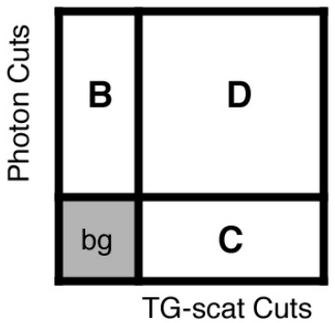
Obtain # of events remaining with Photon-tagged sample (normalization).

Measuring $K_{\pi 2}$ TG-Scatter Background

- Obtain multiple TG-scatter samples using combinations of:
  - CCDPUL: excess 2nd pulse energy
  - B4EKZ: K^+ energy/range matching
  - CHI567: TG π^+ track observed/expected
- Photon-tagged sample ("Normalization") contaminated w/
  - $K_{\pi 2}$ scatters in Range Stack
  - $K^+ \to \pi^+\pi^0\gamma$







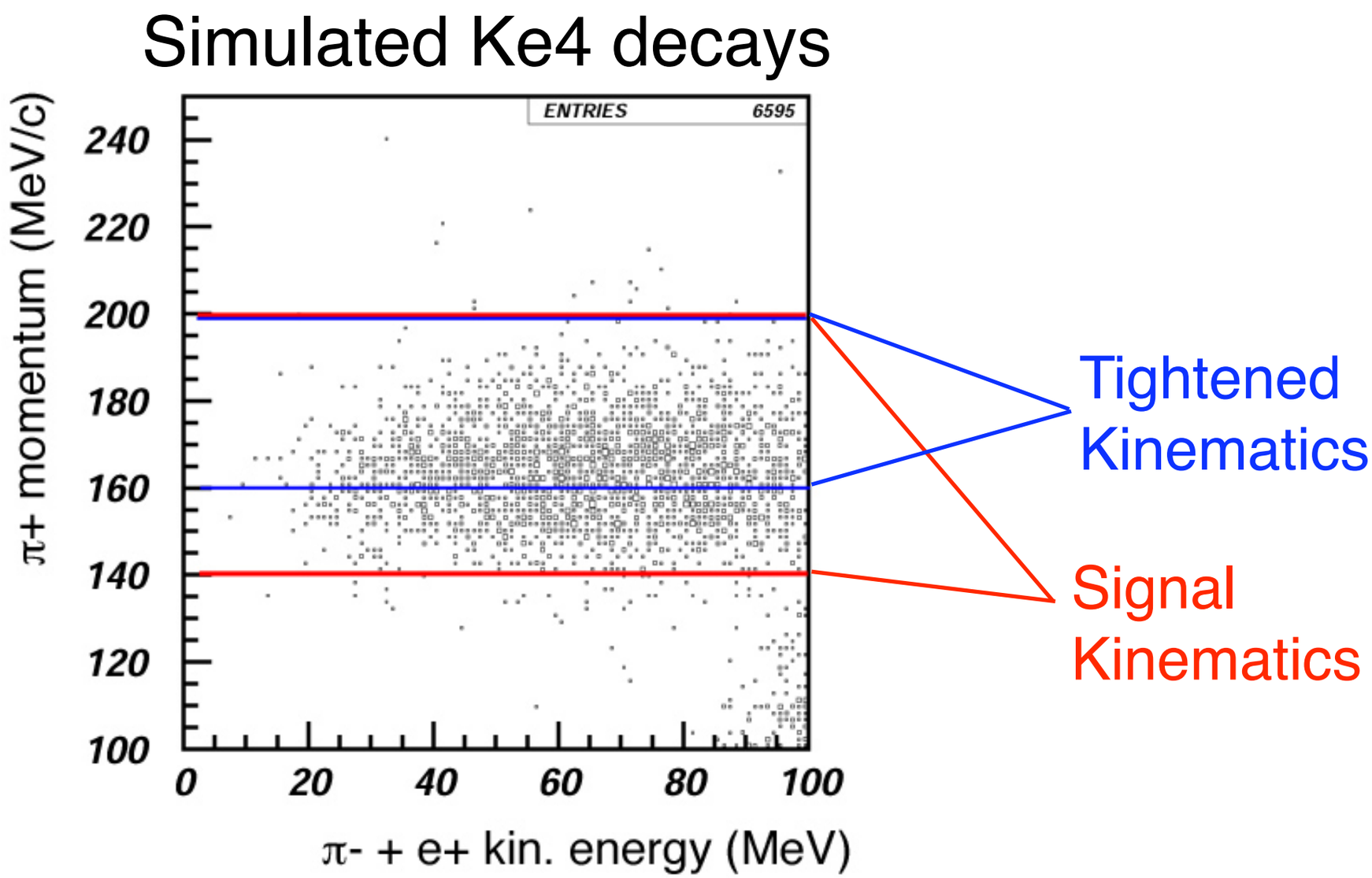
"The enemy of my enemy is my enemy.
Dick Tracy (*Dick Tracy* -1990)

After disentangling the processes:

Process	Background events
$K_{\pi 2}$ TG-scatter	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS-scatter	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$

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

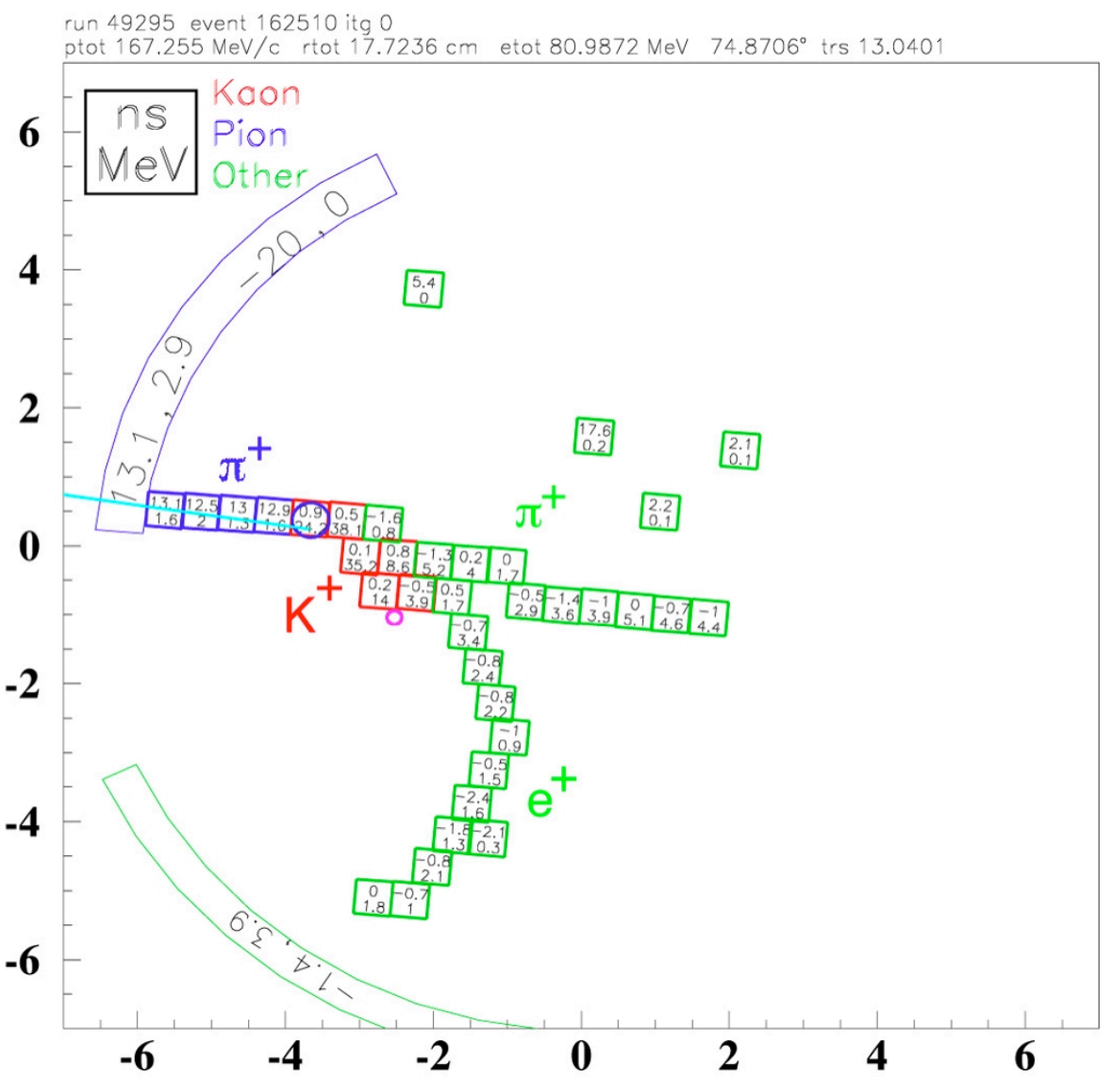
- $K^+ \to \pi^+\pi^-e^+\nu$ can be a background if the π^- and e^+ go undetected.
  - i.e. have very little kinetic energy.

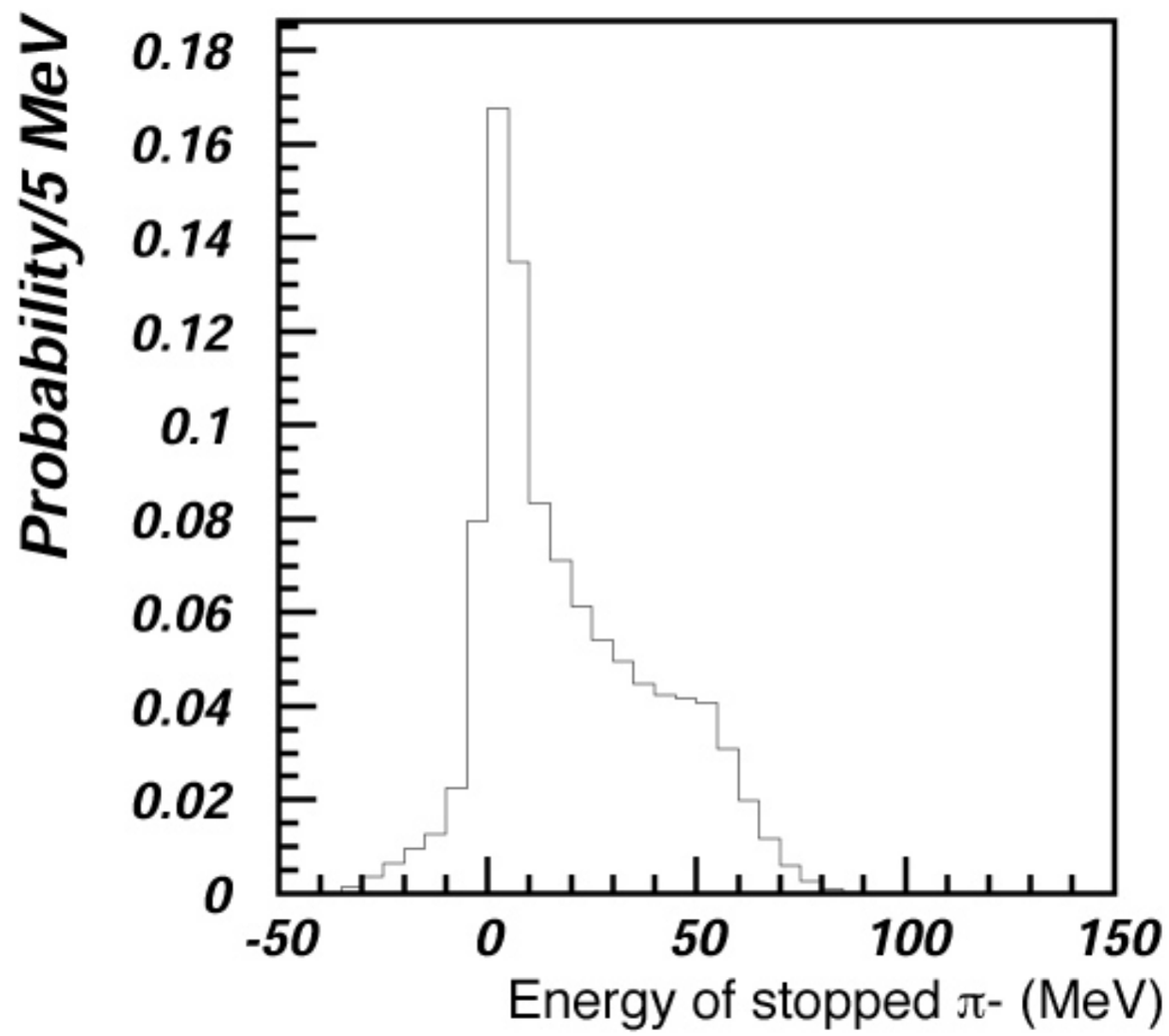


$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4}) Background

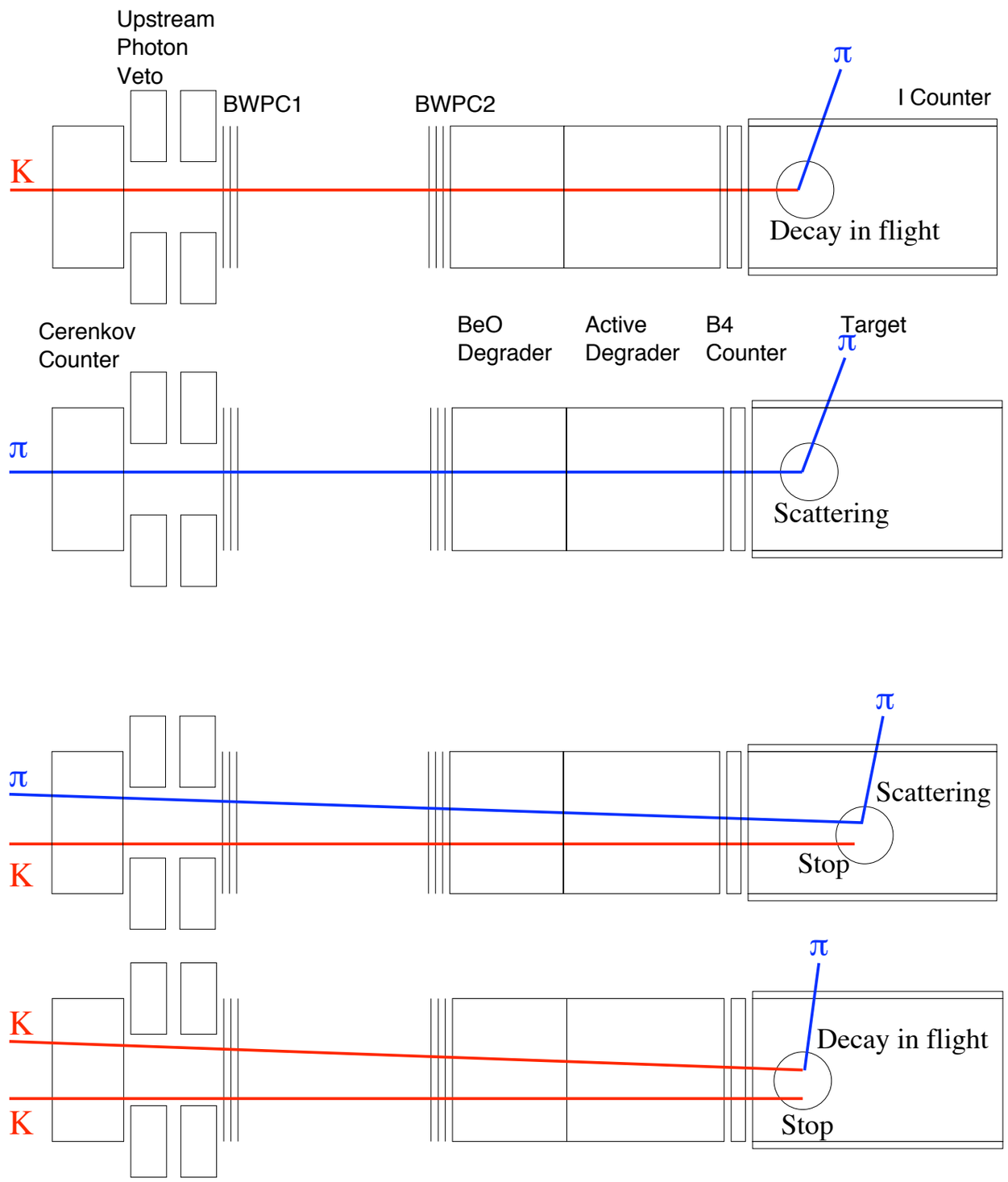
- Obtain Ke4 sample by target-pattern recognition.

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





Beam Background



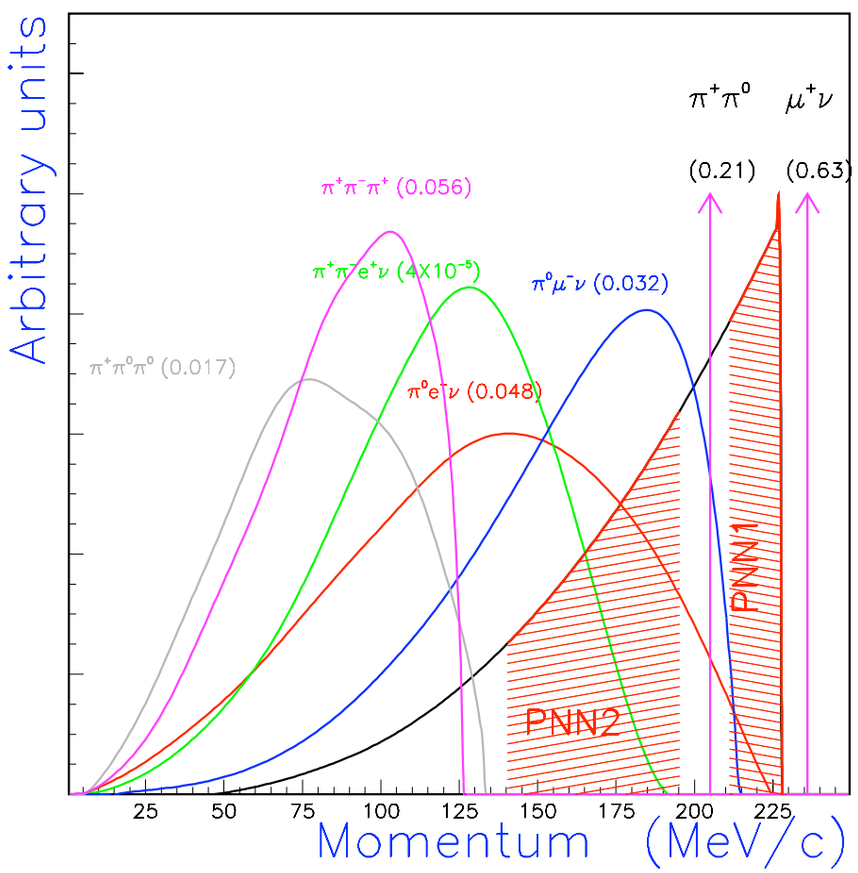
Muon Background

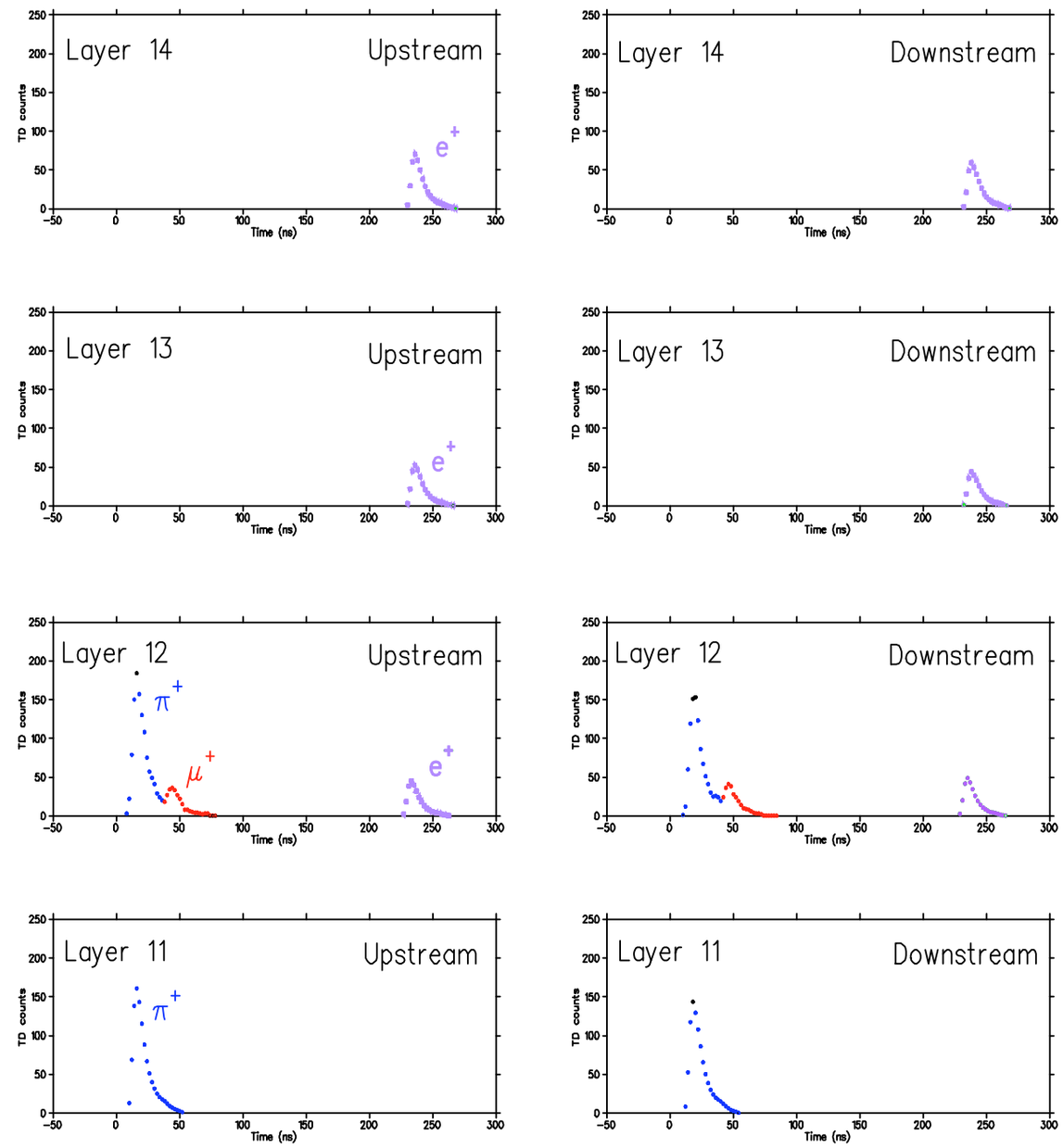
- pnn2 analyses showed that muon background due to:

$$K^+ \to \mu^+\nu,\ K^+ \to \mu^+\nu\gamma \text{ and } K^+ \to \mu^+\pi^0\nu$$

was small (< 0.01 events).

- The criteria on identification of $\pi^+ \to \mu^+ \to e^+$ decay chain was loosened for a 10% gain in acceptance.





$$\pi^+ \to \mu^+\nu_\mu \to e^+\bar{\nu}_e\nu_\mu$$

Total Background and Sensitivity

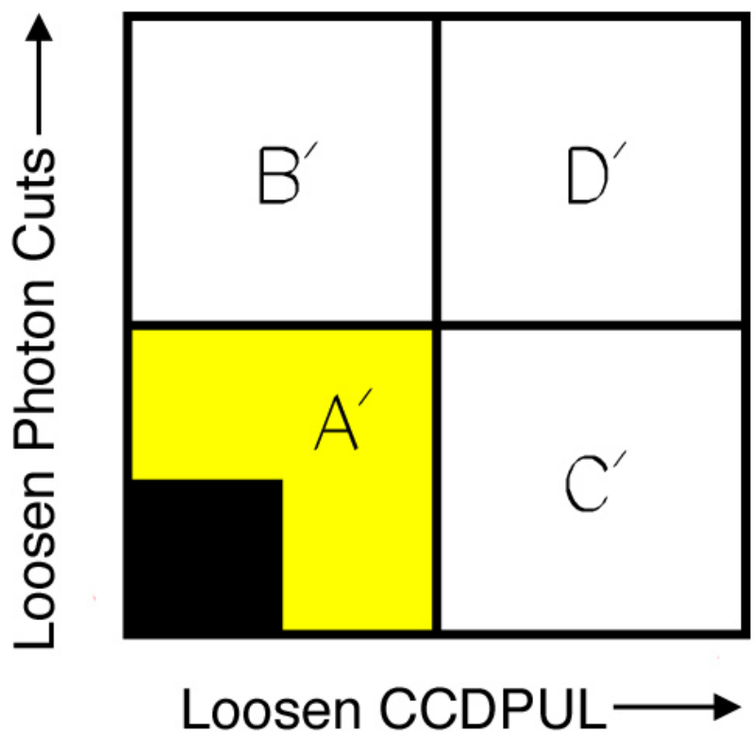
Bkgd Process	Bkgd Events E949	Bkgd Events E787
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 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 $= 0.63 \times 10^{-10}$.

Verify Backgrounds

- Keep signal region blind.
- Loosen Photon cuts & CCDPUL.
- Compare expected events (N_{exp}) to observed events (N_{obs}).
- If cuts are uncorrelated, then (expected/observed) should agree.



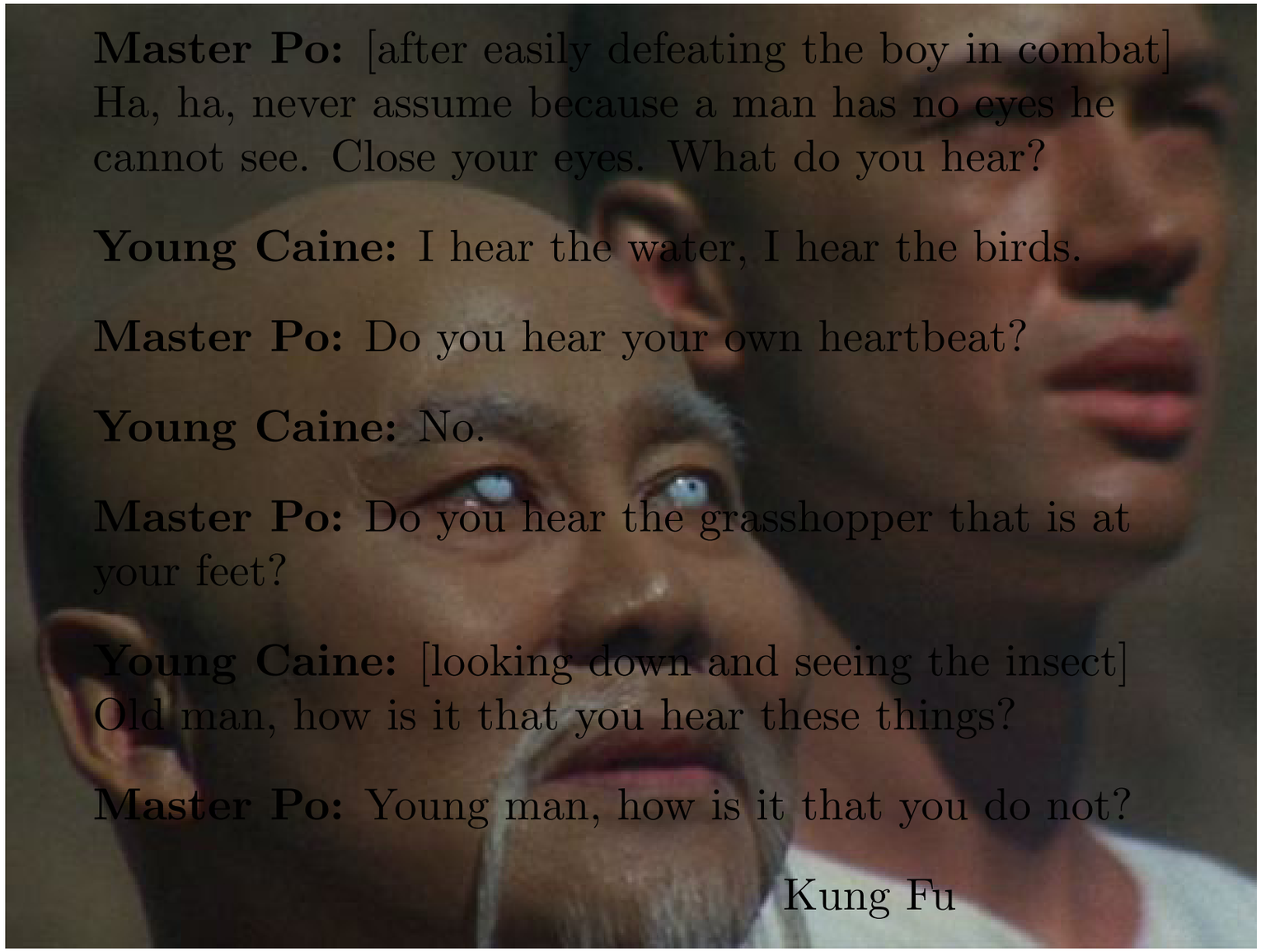
Region	$N_{\rm exp}$	$N_{\rm obs}$
CCD_L	$0.79^{+0.46}_{-0.51}$	0
PV_L	$9.09^{+1.53}_{-1.32}$	3
PV_{looser}	$32.4^{+12.3}_{-8.1}$	34

- 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_L and PV_L given the expectation is 5%; the expectation is [2%,14%] when the uncertainty in $N_{\rm exp}$ is taken into account.

Tightened Regions

- Backgrounds not uniformly distributed.
- Four cuts were tightened to further divide signal regions.
  - Delayed Conincidence.
  - $\pi \to \mu \to e$ cuts.
  - Kinematic box.
  - Photon cuts.
- 9 cells chosen
  - differing levels of signal acceptance (S_i) and background (B_i).
- Calculate $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ using S_i/B_i of any cells containing events using the likelihood ratio method.

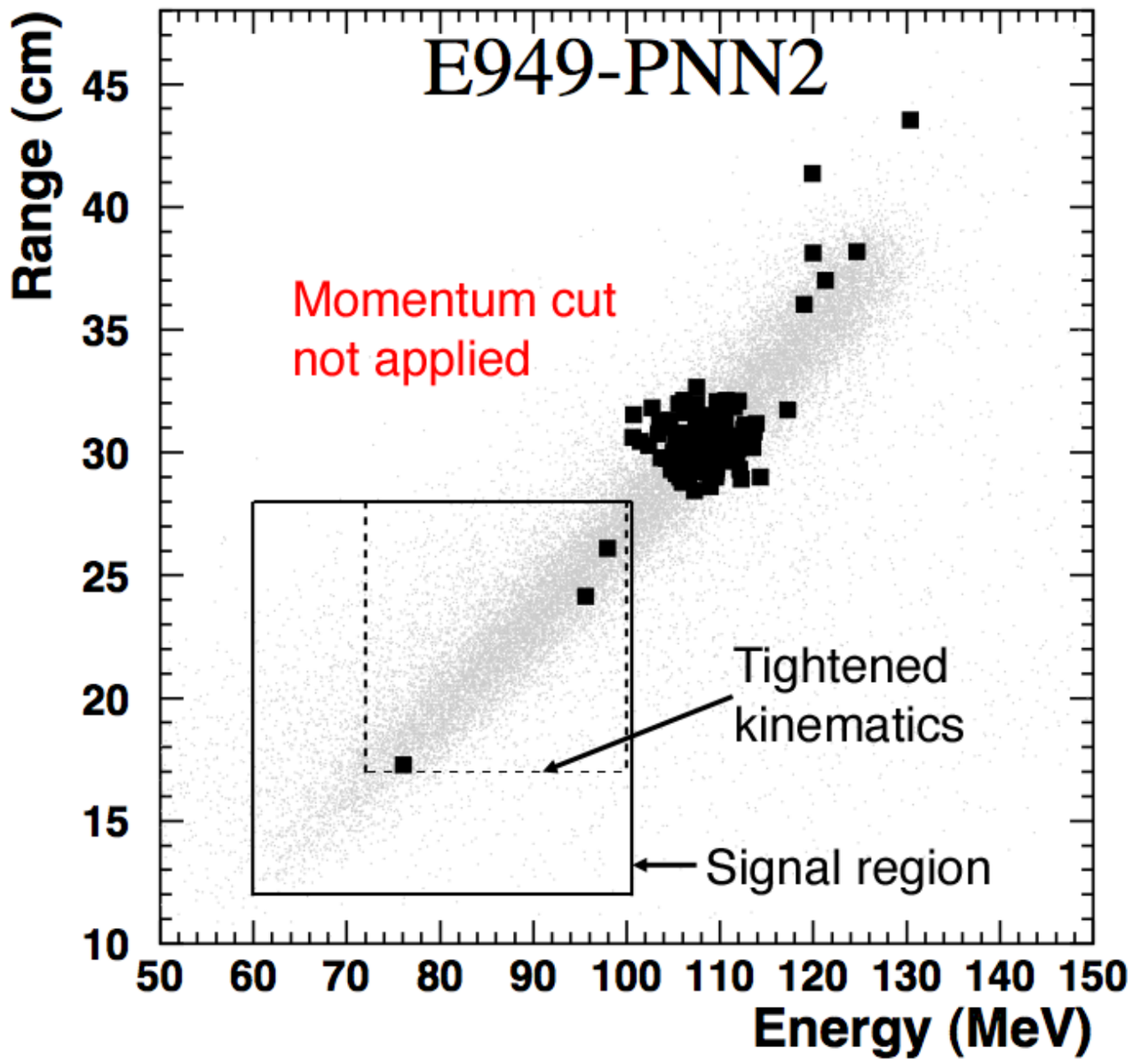
Signal Region



The nine cells

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

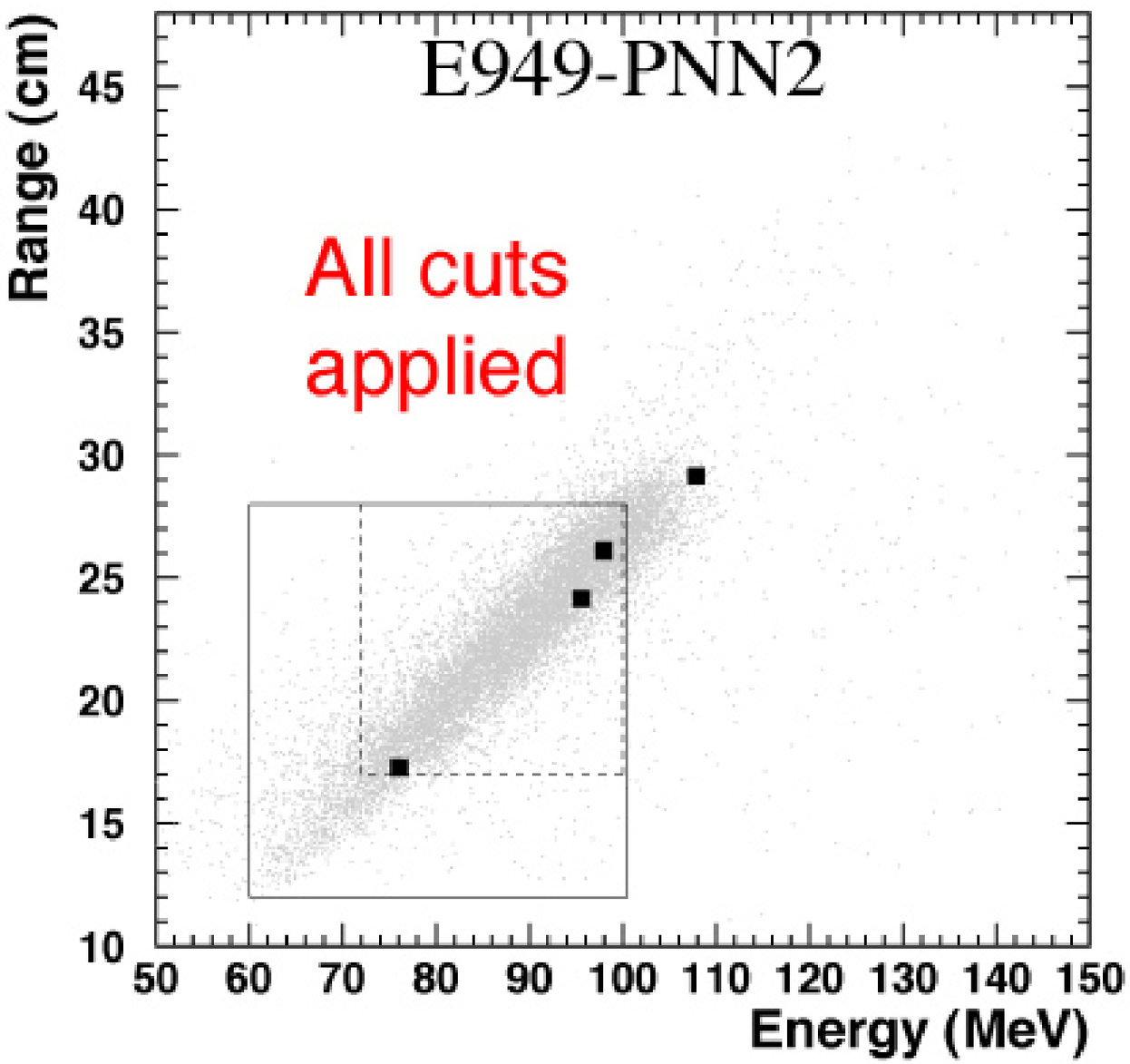
Signal Region



The nine cells

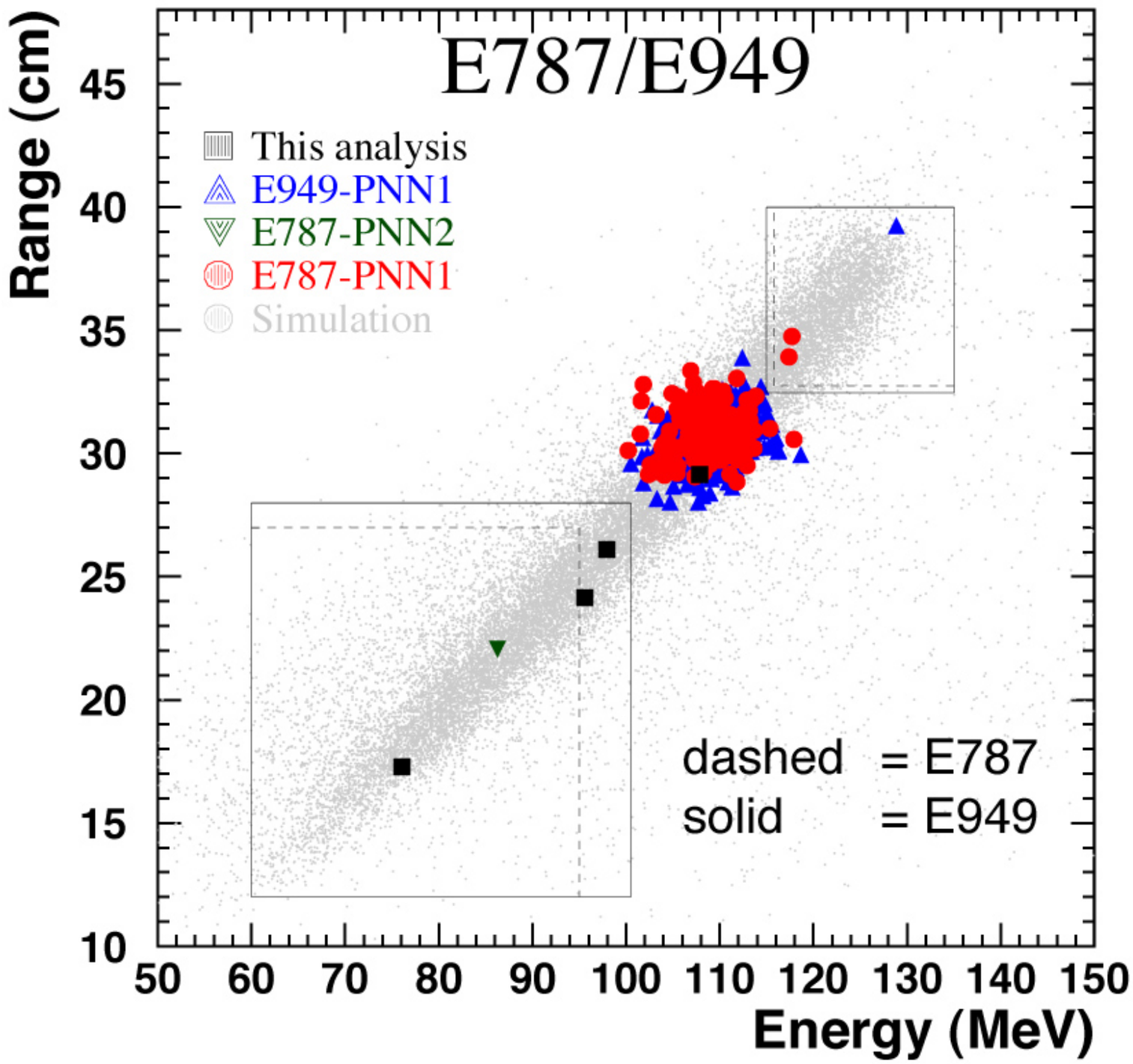
Bkgd	Events	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20

Signal Region



- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$
- The probability of all 3 events to be due to background only is 0.037.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$

All Signal Regions



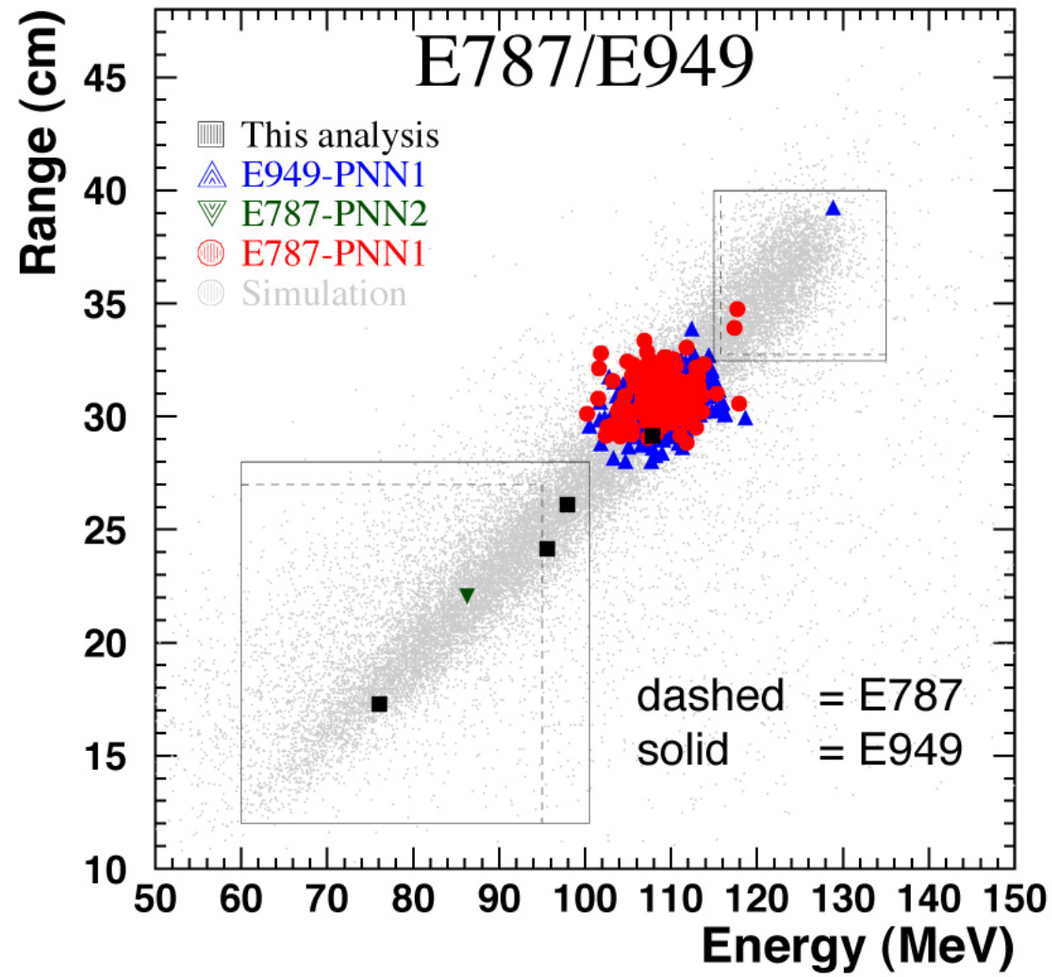
- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
- The probability of all 7 events to be due to background only is 0.001.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$
- Despite the size of the boxes in energy *vs.* range, the pnn1 analyses are 4.2 times more sensitive than the pnn2 analyses

Conclusions

E787+E949

- 25 years (on Oct 17th)
- 3(?) upgrades.
- $\mathcal{B} < 1.4 \times 10^{-7} \rightarrow$
  $\mathcal{B} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
- Standard Model is still the standard.

  - twice as large, but consistent with, the Standard Model expectation of $(0.85 \pm 0.07) \times 10^{-10}$.



extras