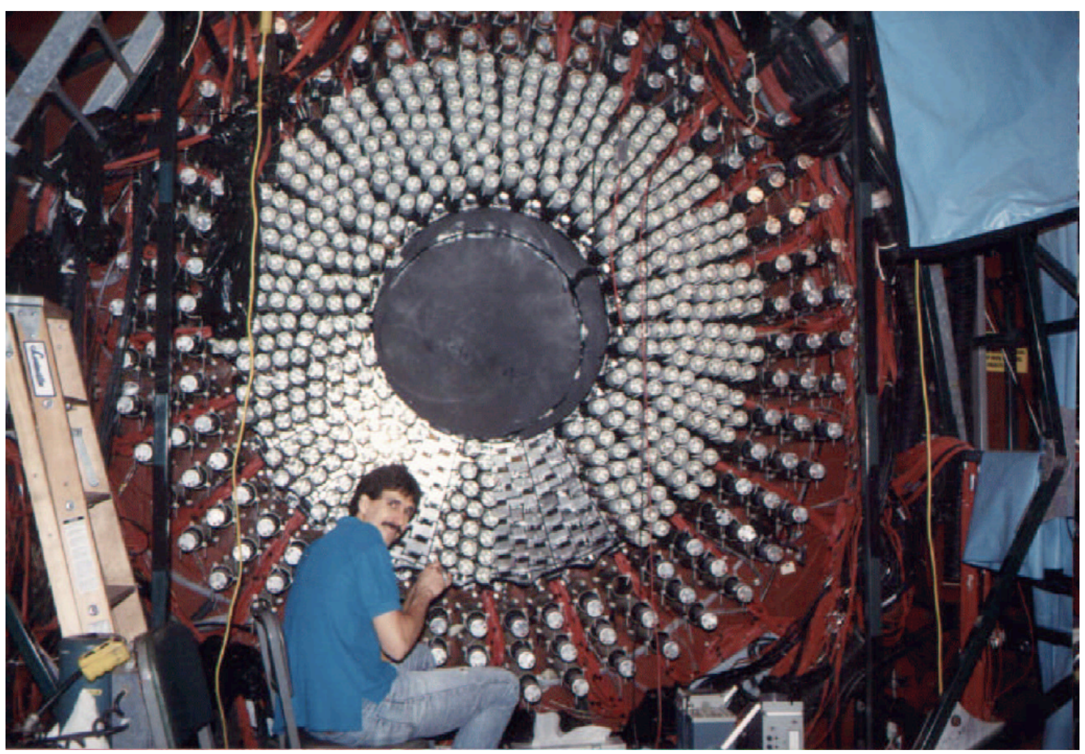
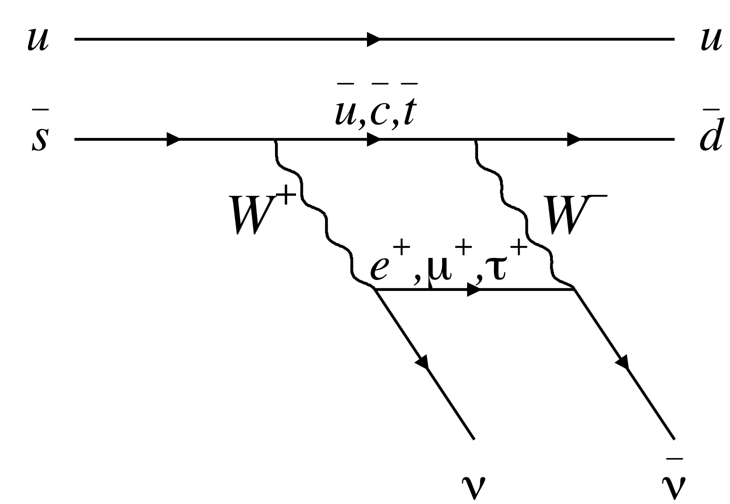
The Quest for the Rare Decay $K^+ \to \pi^+ \nu\bar{\nu}$

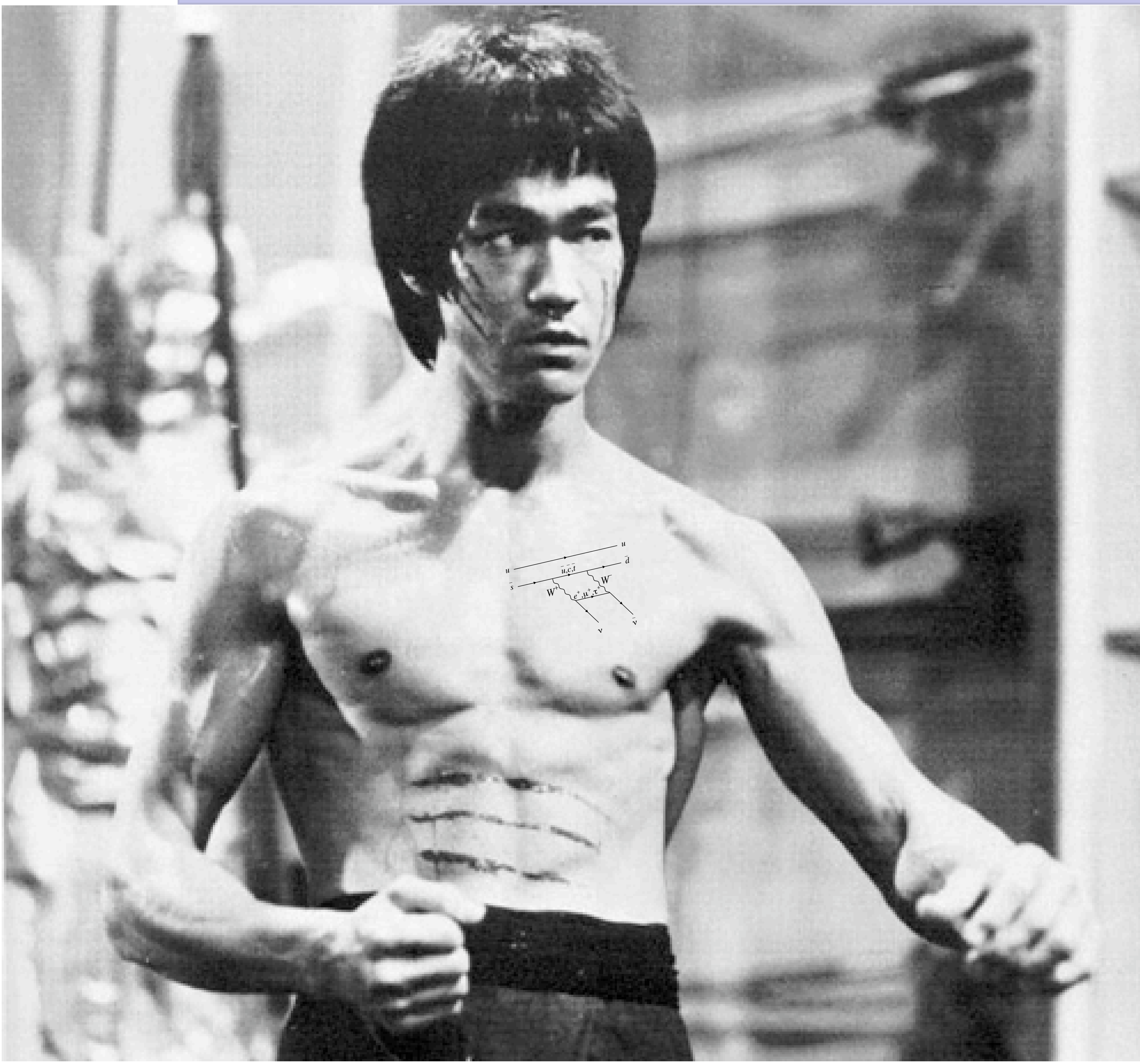
Benji Lewis
University of New Mexico





E949 and the Legend of the Black Box

Alternate Title



E787+E949 Collaboration

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

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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

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

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

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

- Highly Suppressed in SM

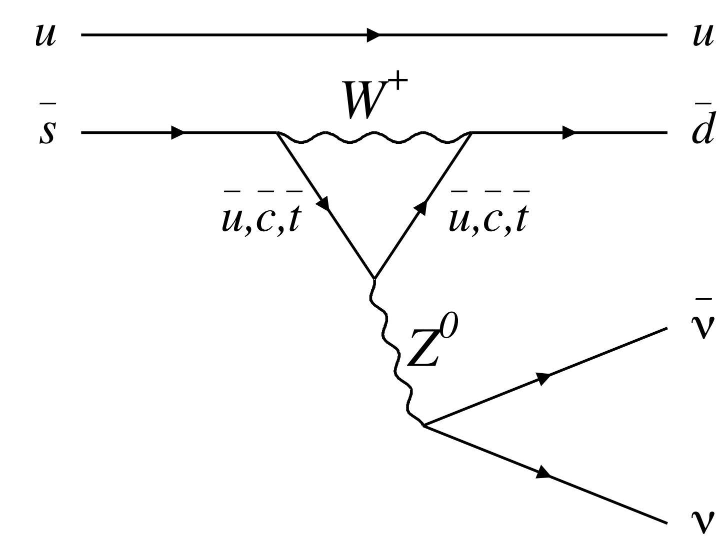
  $m_t >> m_c, m_u$

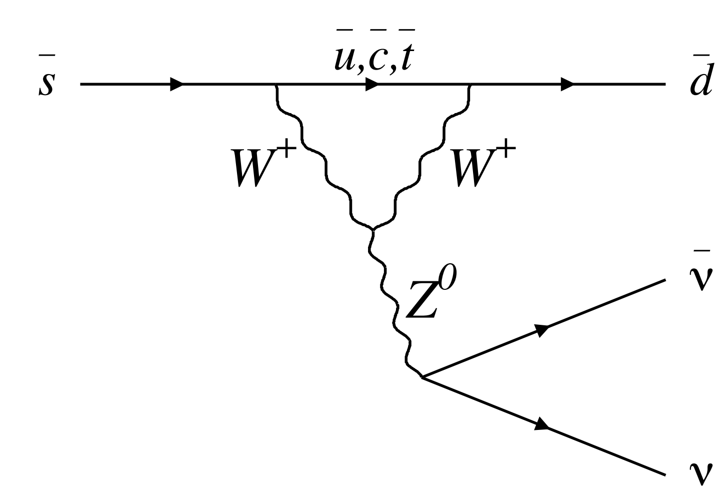
  if $m_t \sim m_c, m_u \implies$ much, much lower BR.

- Theoretically Clean

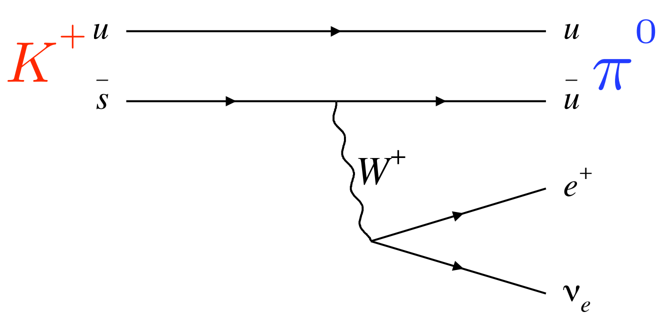
- Branching ratio $\sim 6\%$ precision.

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

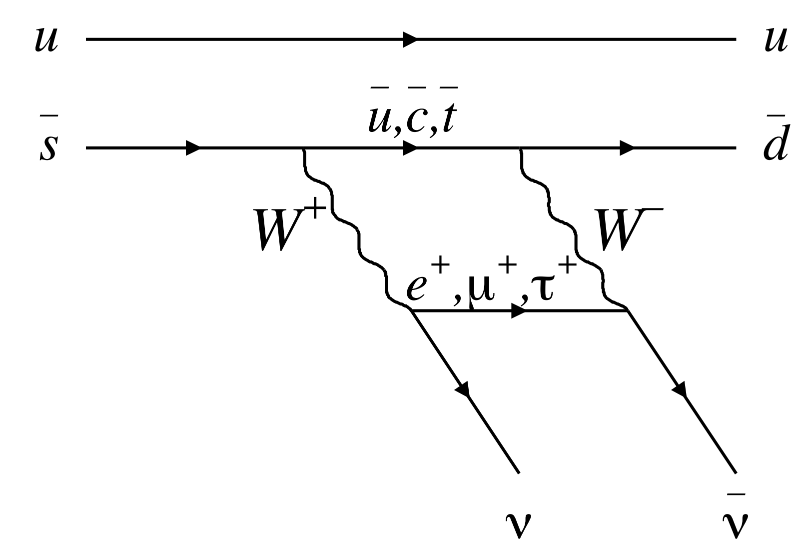




$\mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu_e) = 0.0482$



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



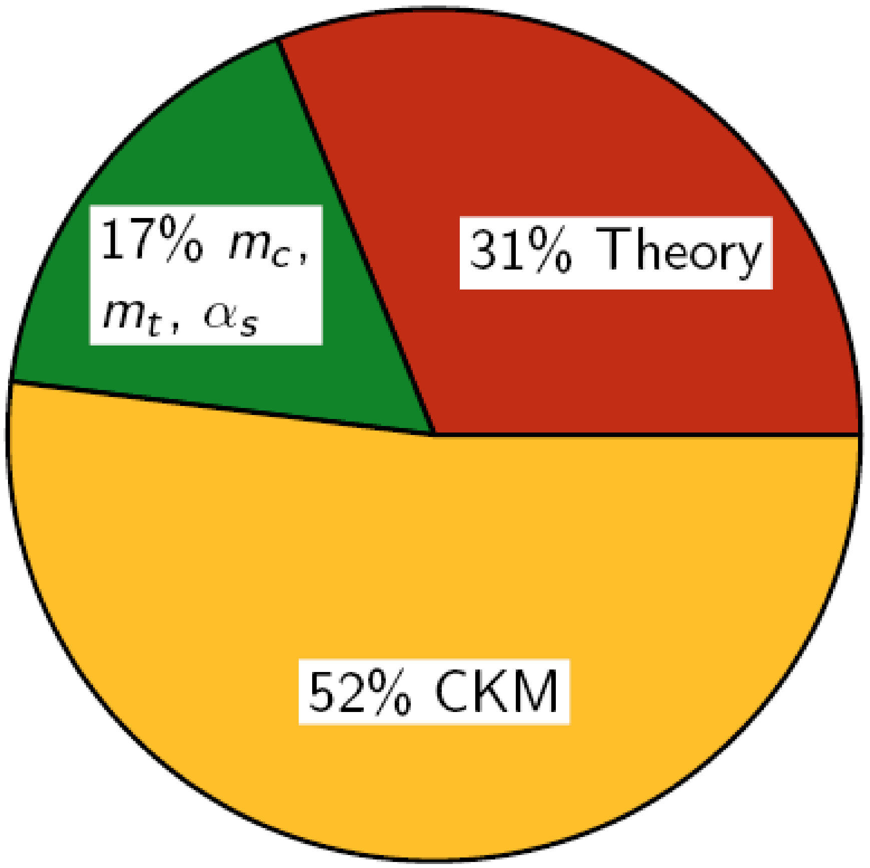
FCNC of $\mathrm{K}^+ \rightarrow \pi^+ \nu \bar{\nu}$ in SM

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

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

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

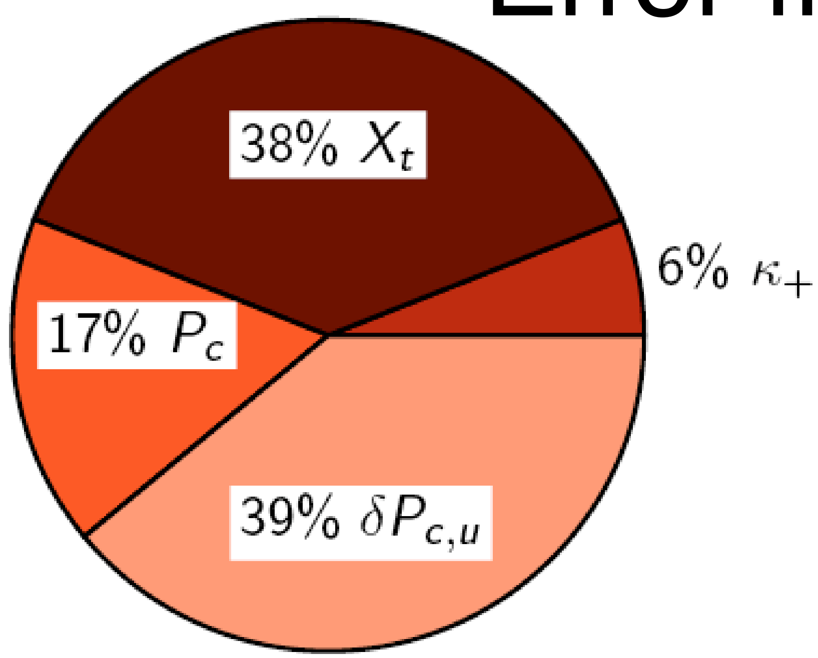
Error in Branching Ratio



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

From Joachim Brod
CKM08

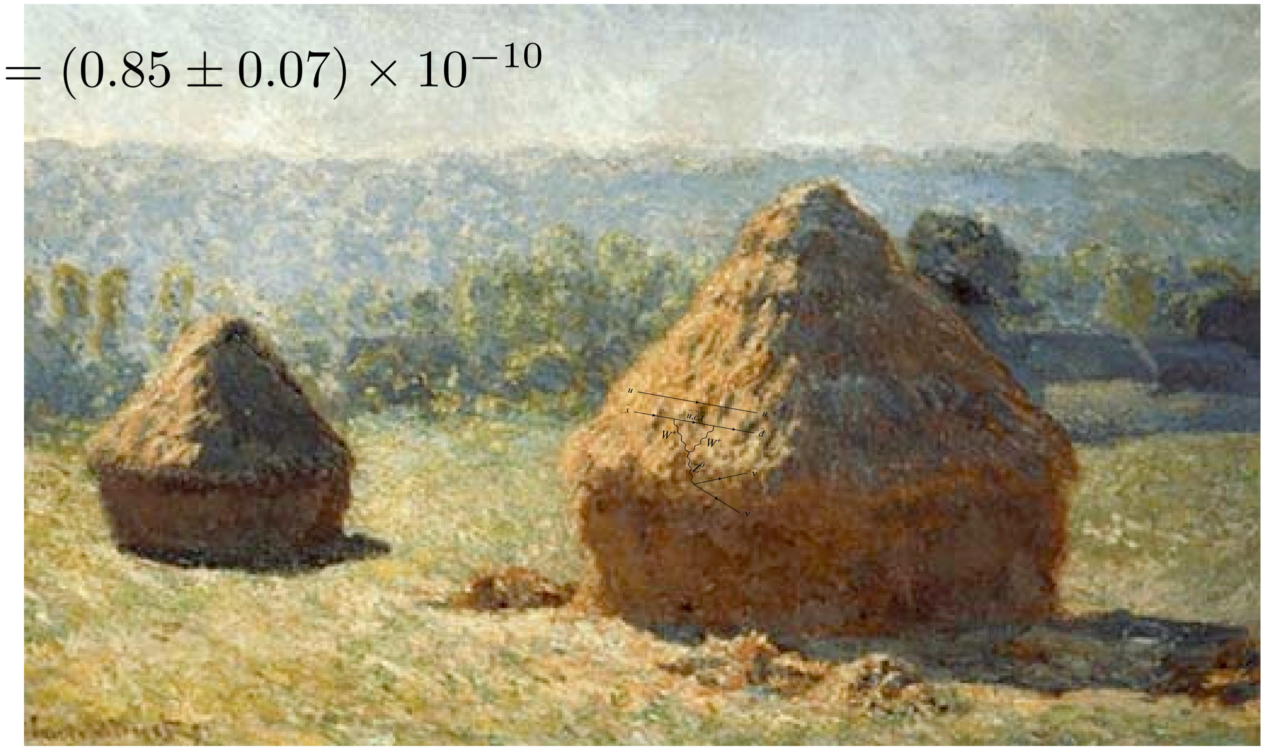
Error from Theory



- Calculate electroweak corrections to X_t [Work in progress]
- Improve on $\delta P_{c,u}$ by a lattice calculation [Isidori et al. '06]
- With better $K_{\ell 3}$ data improve on κ_+ [Mescia, Smith '07]

Finding a needle

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

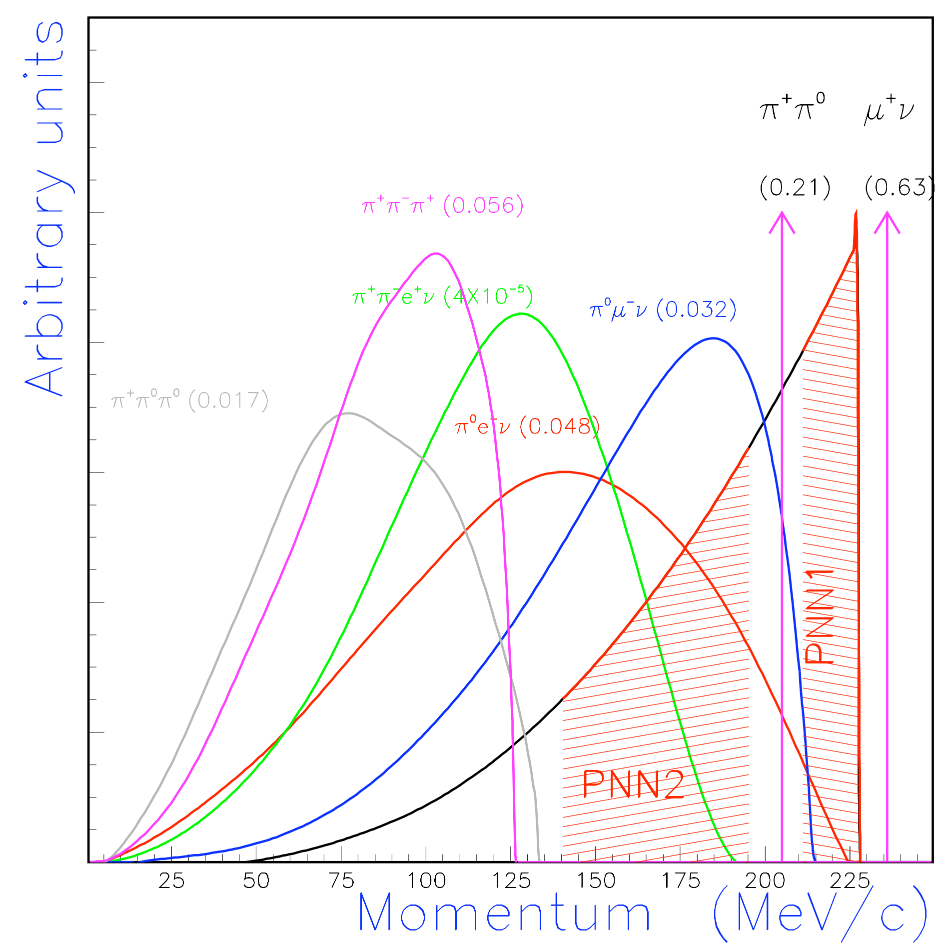


Claude Monet
Wheatstacks (End of Summer).
1890. Oil on Canvas.
Art Institute of Chicago

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

- Must have a K^+.
- Outgoing π^+ track.
- No chance of observing ν or $\bar{\nu}$.
- A stopped K^+ experiment:
  - Delayed Coincidence
  - Specific kinematic regions

    PNN1/PNN2



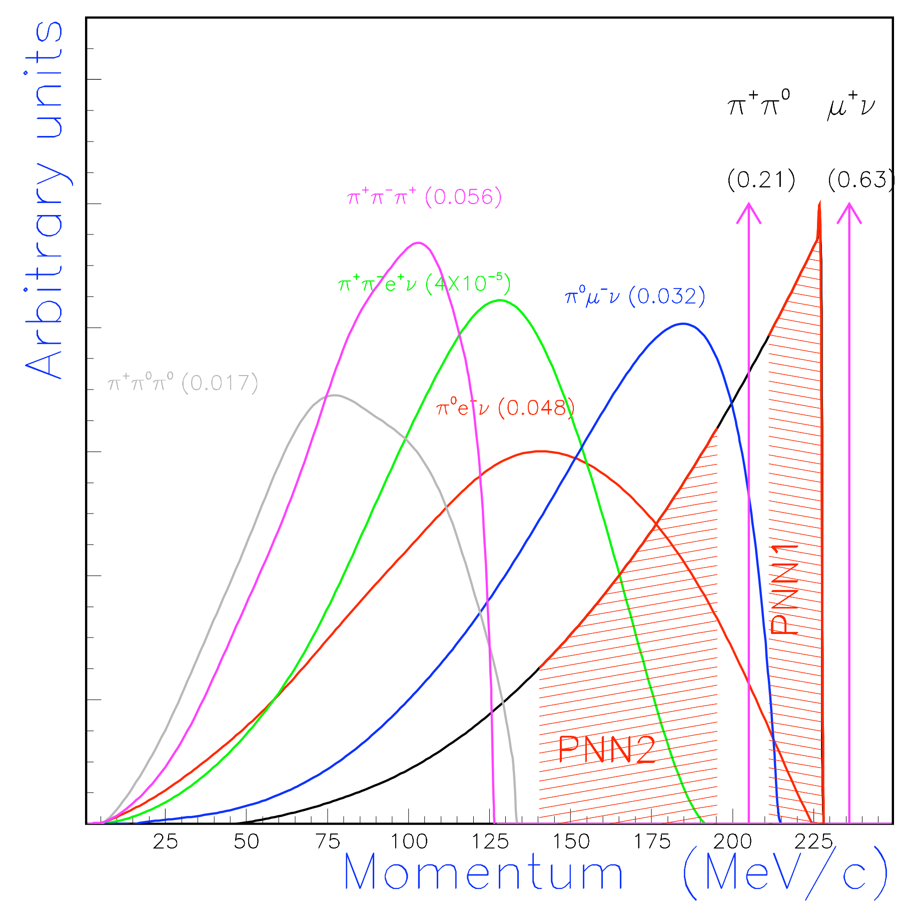
Possible Backgrounds

Shock & Awe Slide

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]	

- What is the kinematics of charged track? (Track Kin.)
- Any additional charged tracks? (Extra Energy)
- Have delayed coincidence (DC)?
- Is charged track a π^+ (Particle ID)?
- Any photons?



K^+ beam

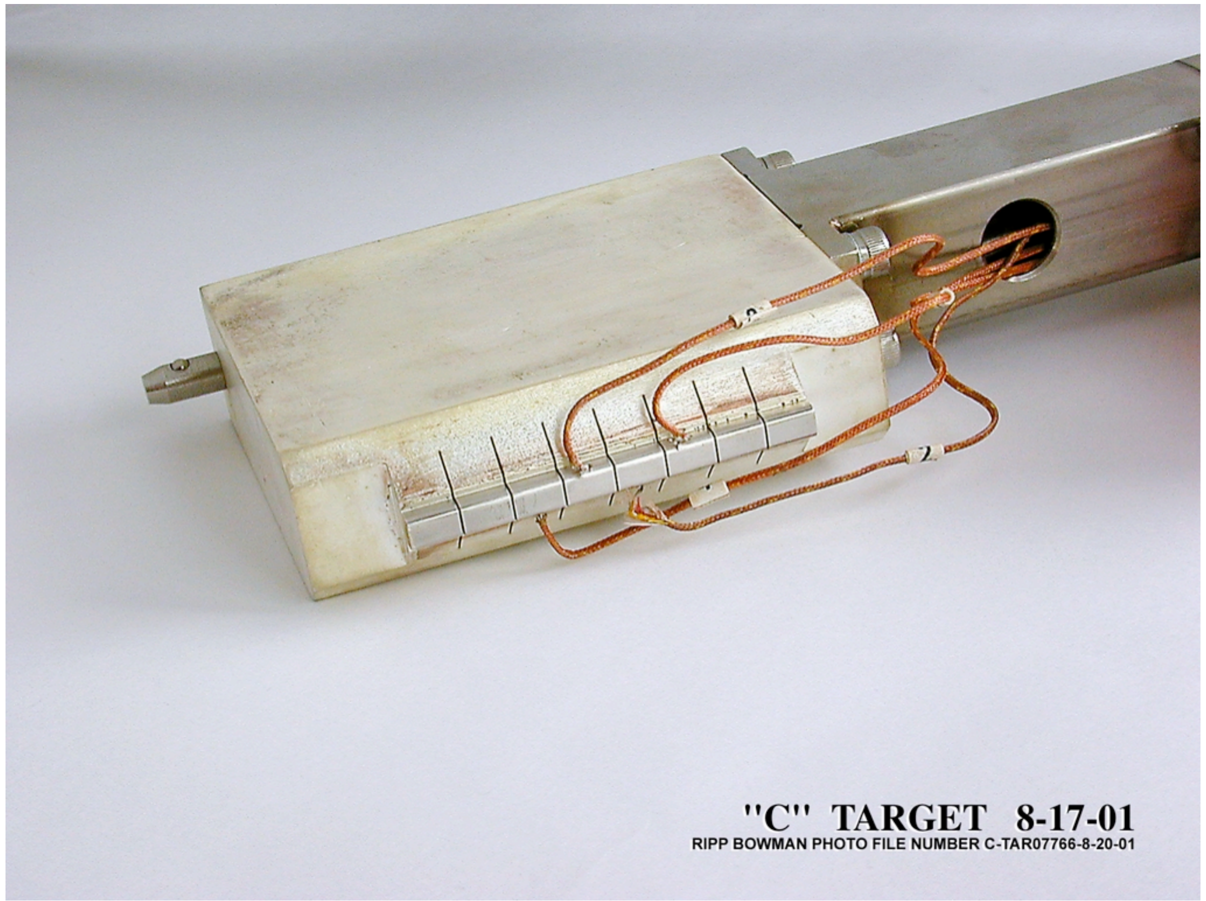
- 65×10^{12} @ 24 GeV/c Protons on production target

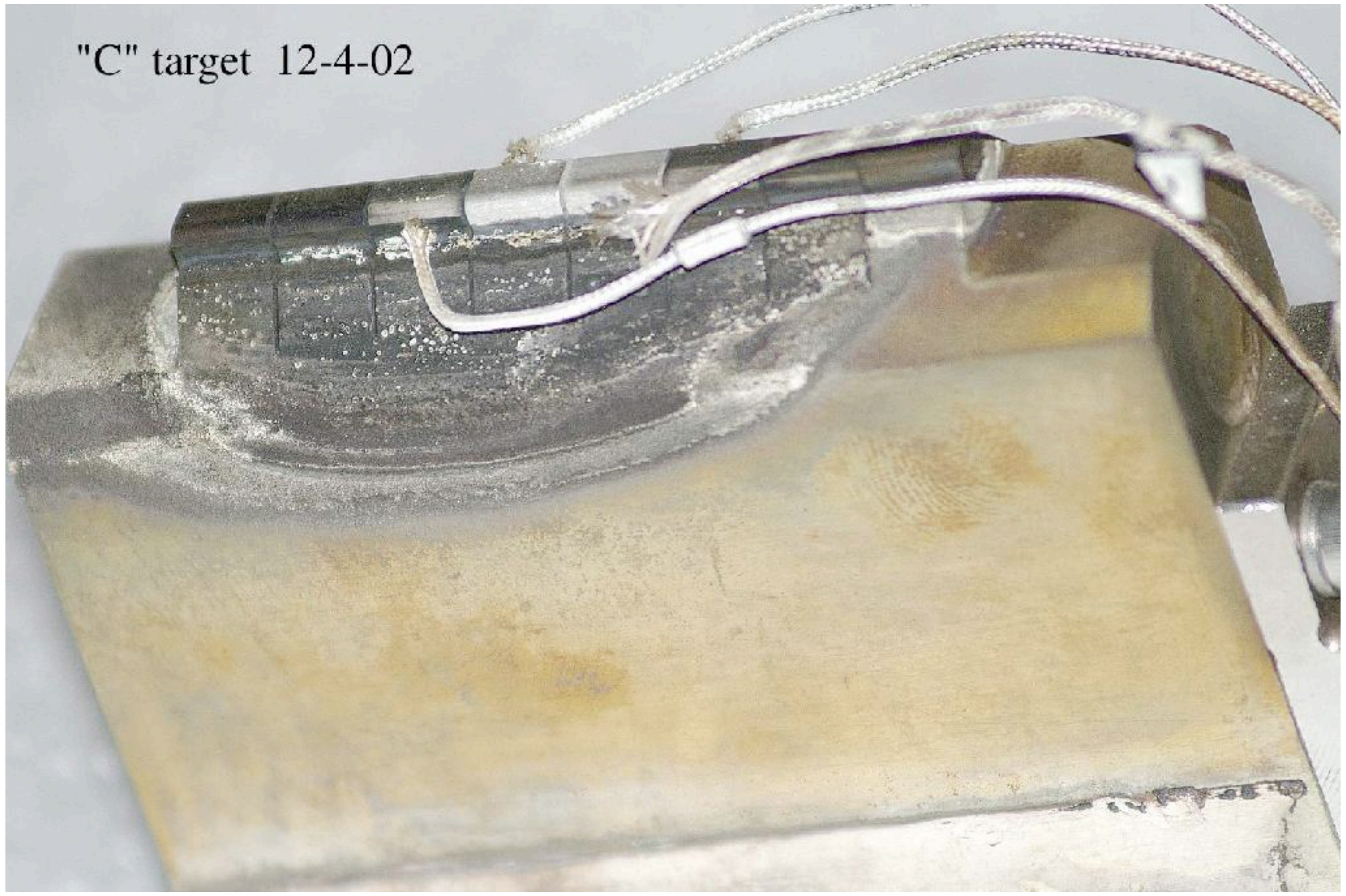
  2 sec 'spill' every 5 sec

  3.5×10^6 K^+ per spill

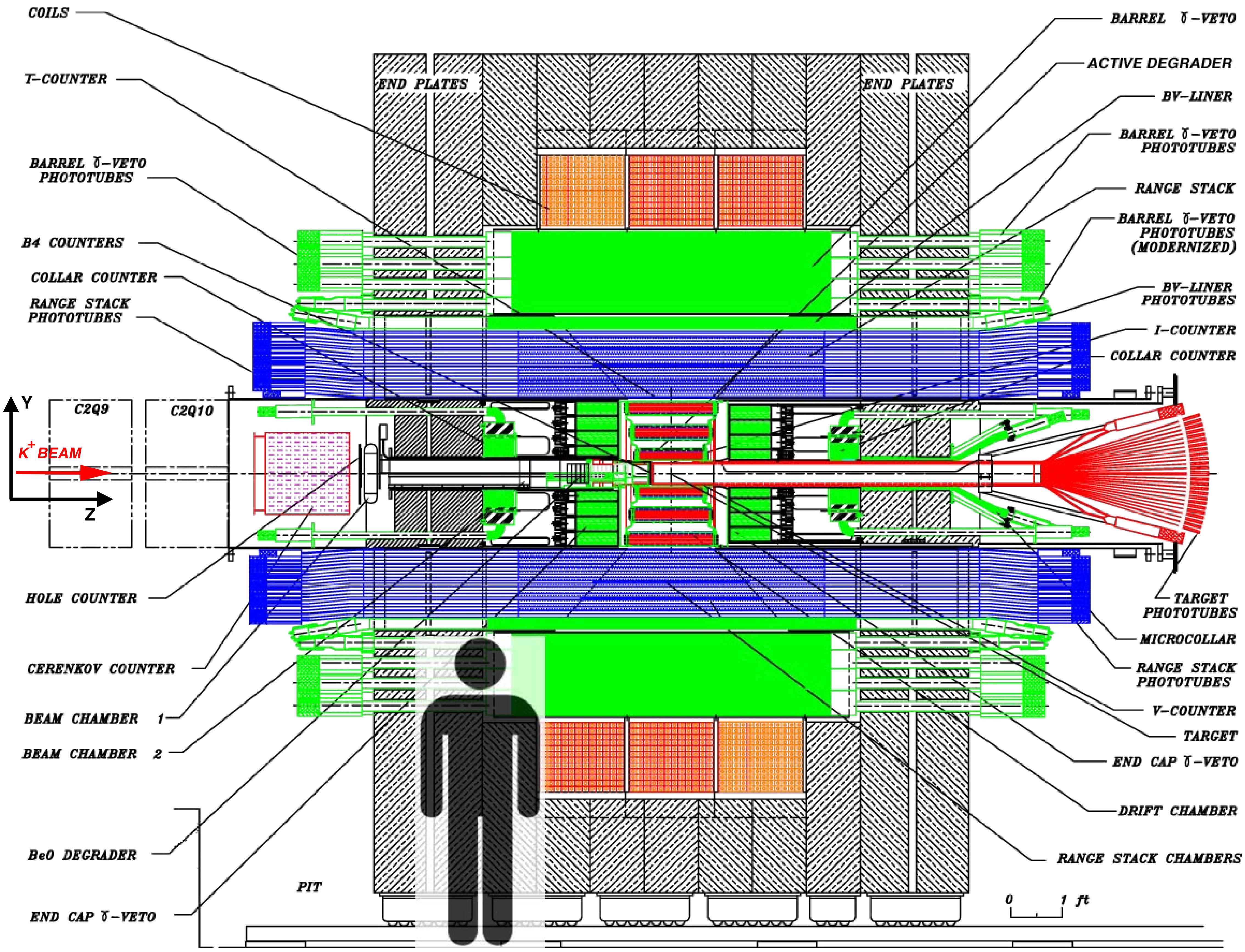
  ~ 710 MeV/c K^+ beam

- Electrostatic Separators $\Longrightarrow$ $K^+ : \pi^+$ of 3:1





E949 Detector



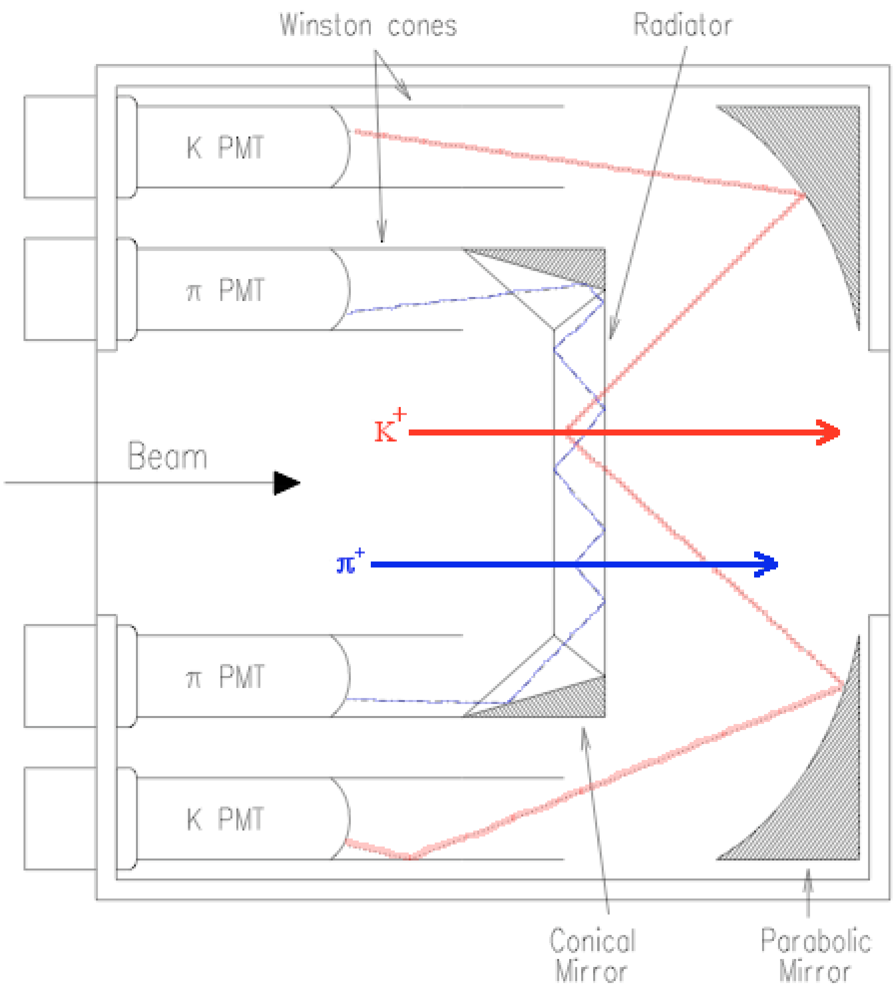
Detecting the K^+ beam

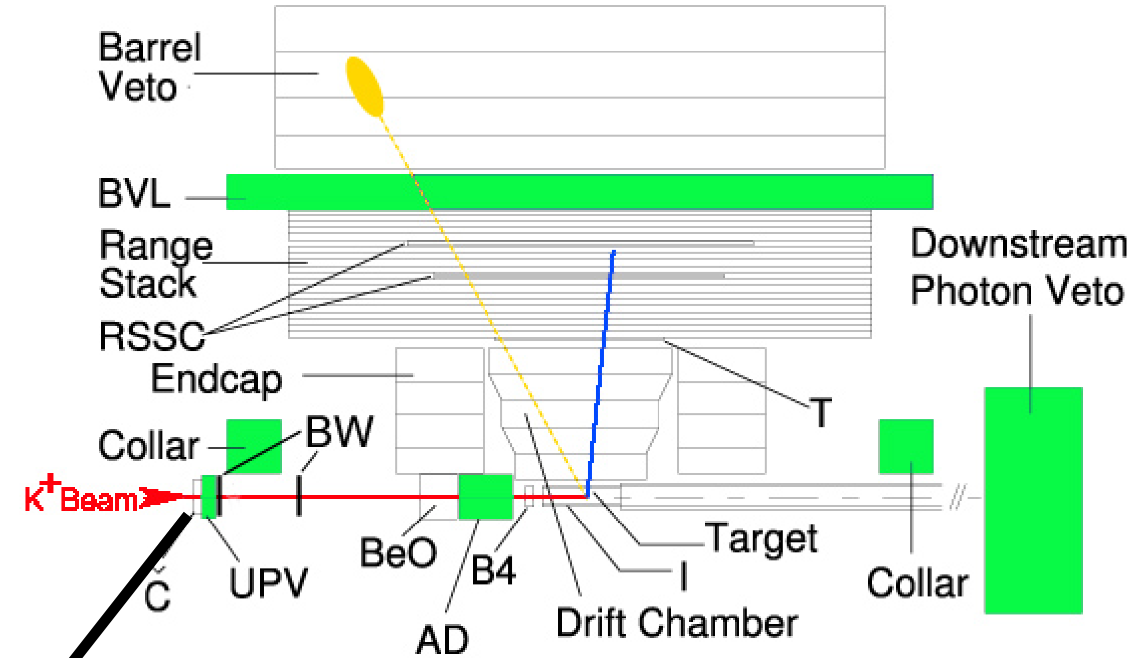
Čerenkov Detector

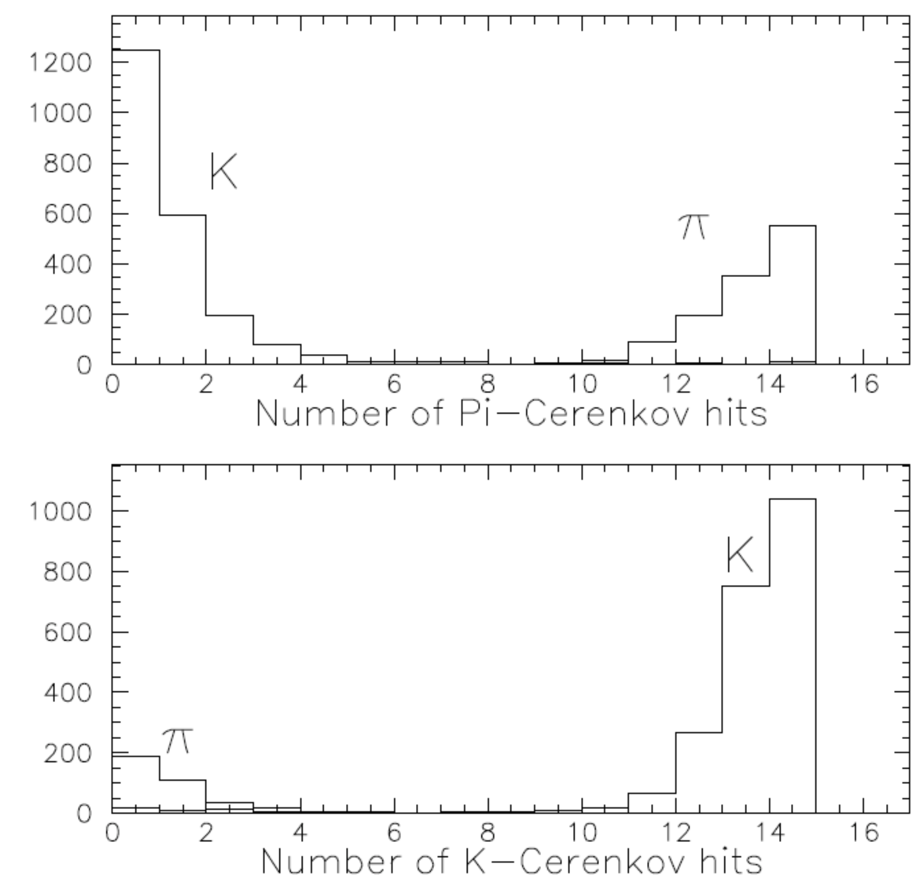
- Particle Identification
  - ID Beam K^+ & π^+

    We dislike extra beam particles at K^+ (beam) time and decay time.

- Counts total # of K^+.

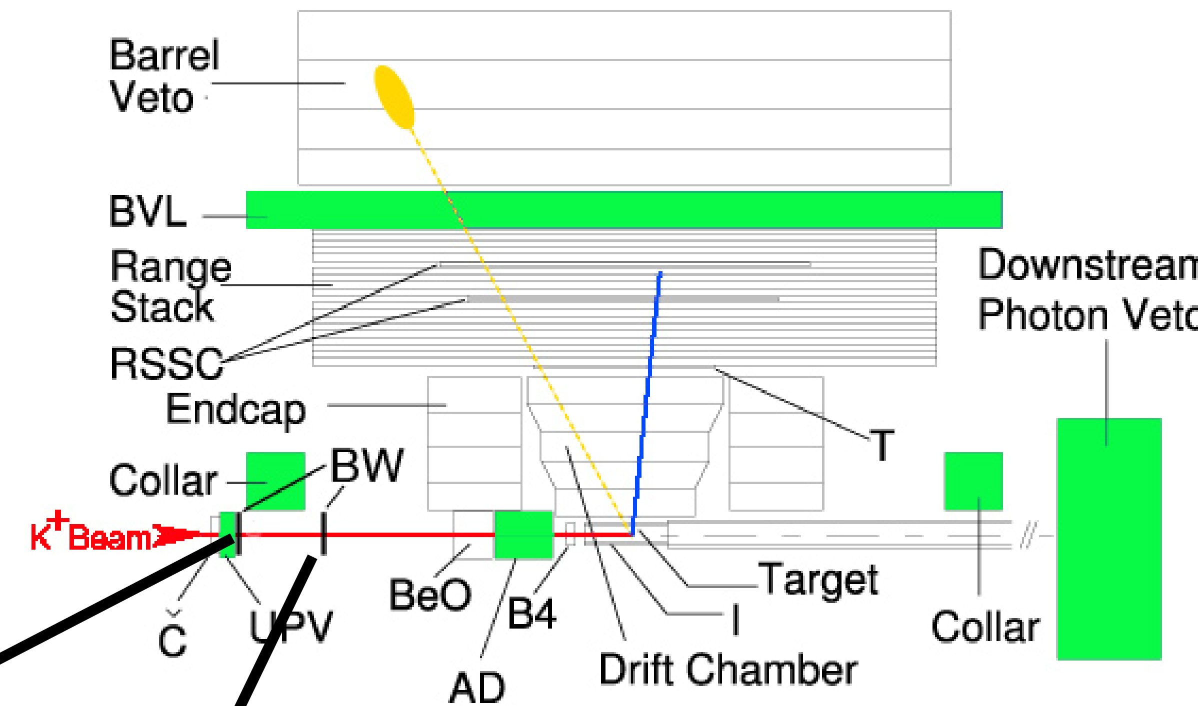


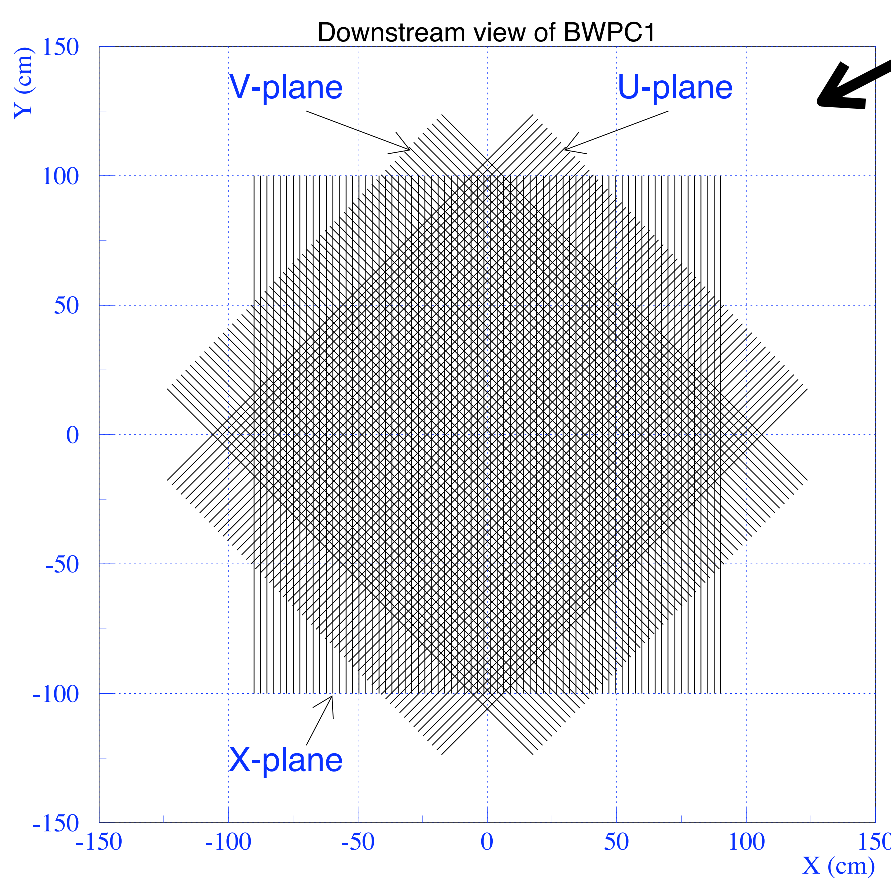


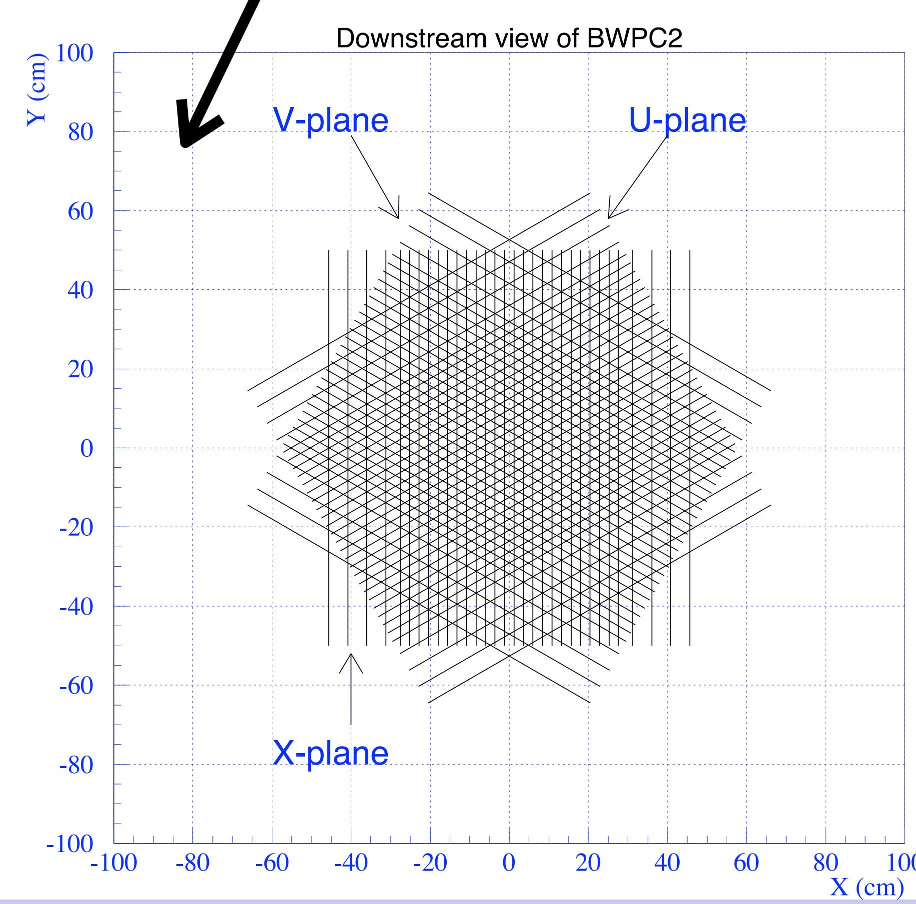


Beam Wire Proportional Chambers

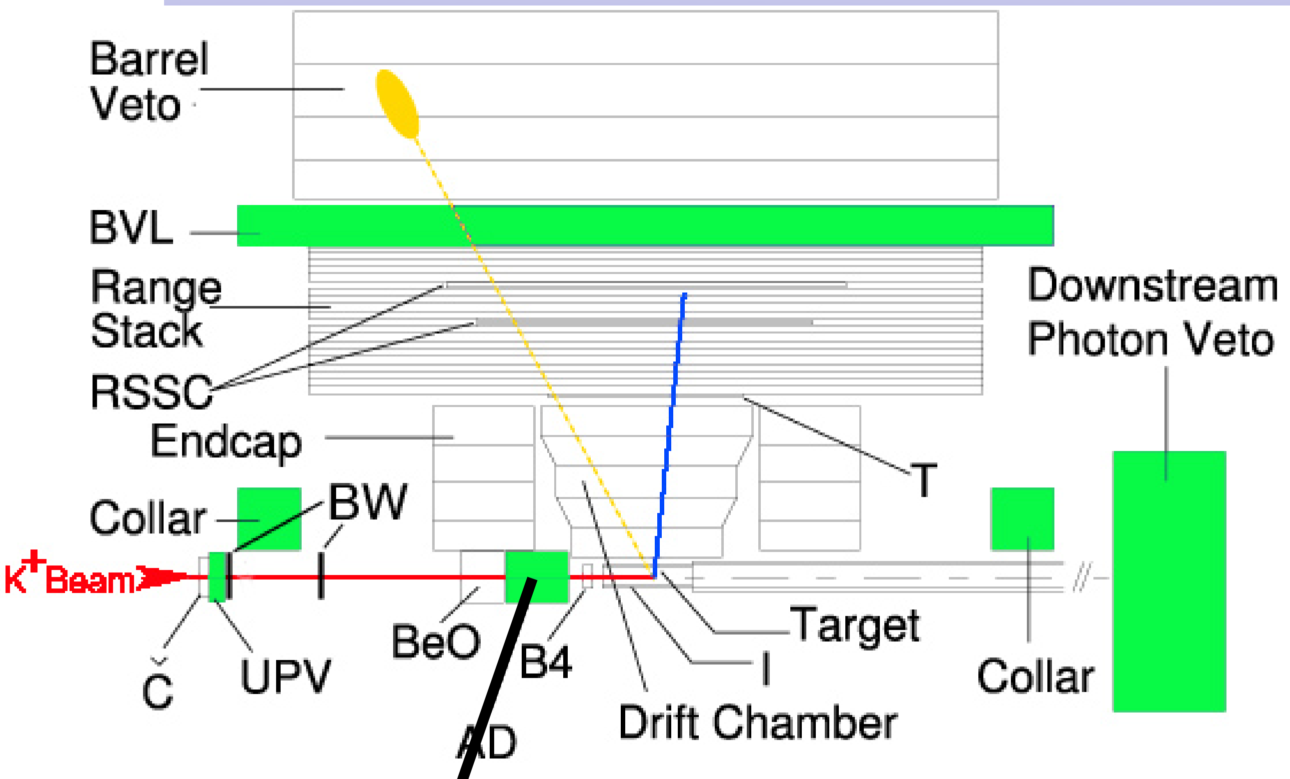
- Detects all charged particles.
  - No particle discrimination (K^+ or π^+ ?).
- Good $x - y$ resolution (and z).
- ID's additional beam particles.

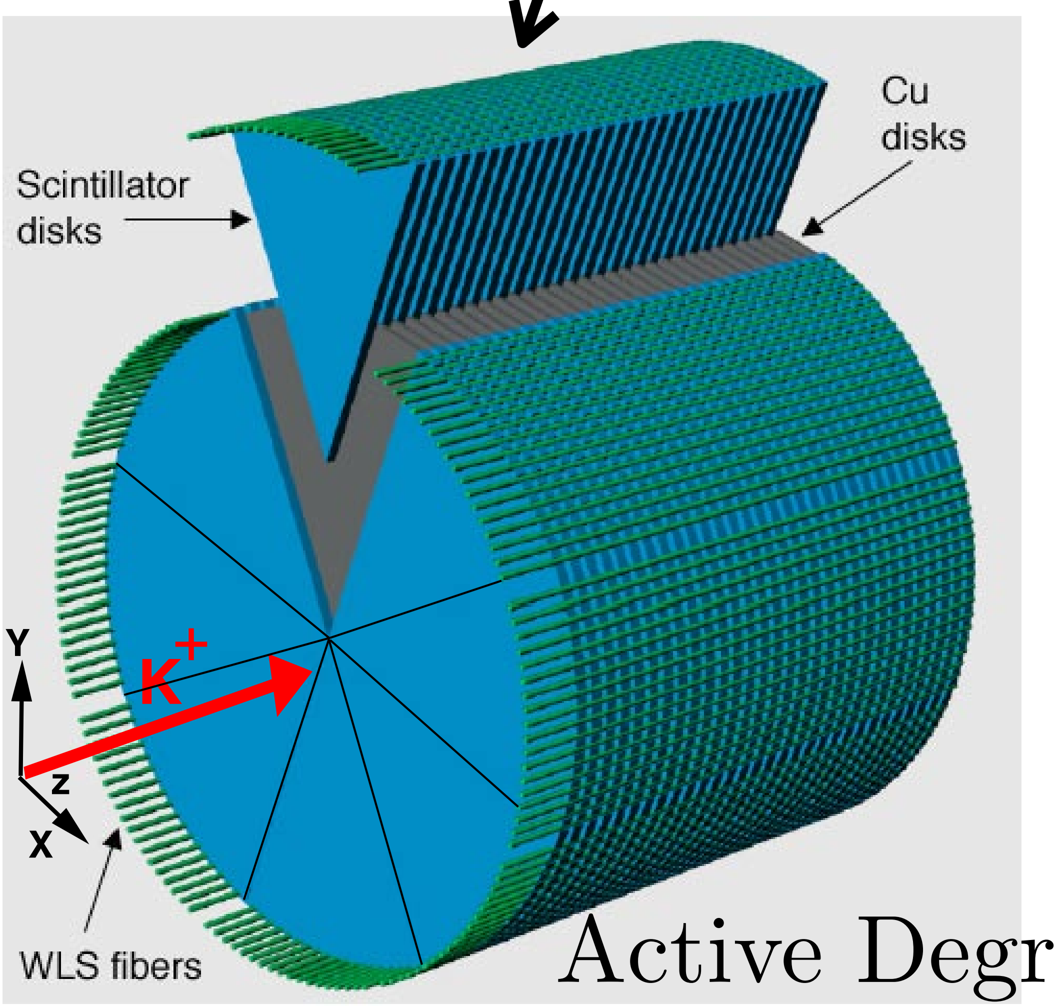






Detecting the K^+ beam





Active Degrader

Inactive Degrader

- 11.1cm of BeO.
- Slows down K^+'s

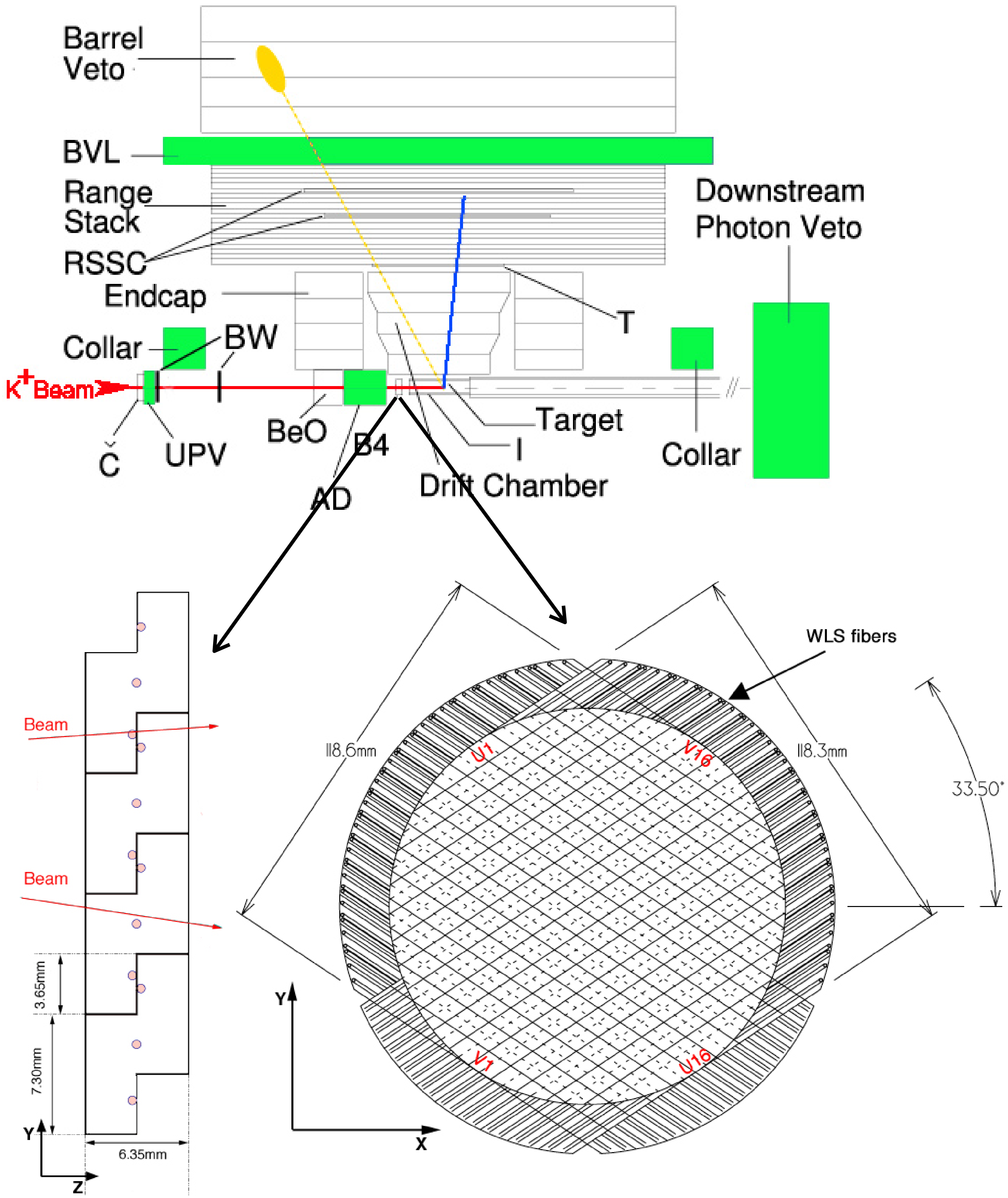
Active Degrader

- 40 layers of 2mm scintillator disks alternating with 2mm Copper disks

  Total z-thickness $\sim$ 16cm

- Slows down K^+'s
- Measures deposited energy.
- Poor $x - y$ resolution.

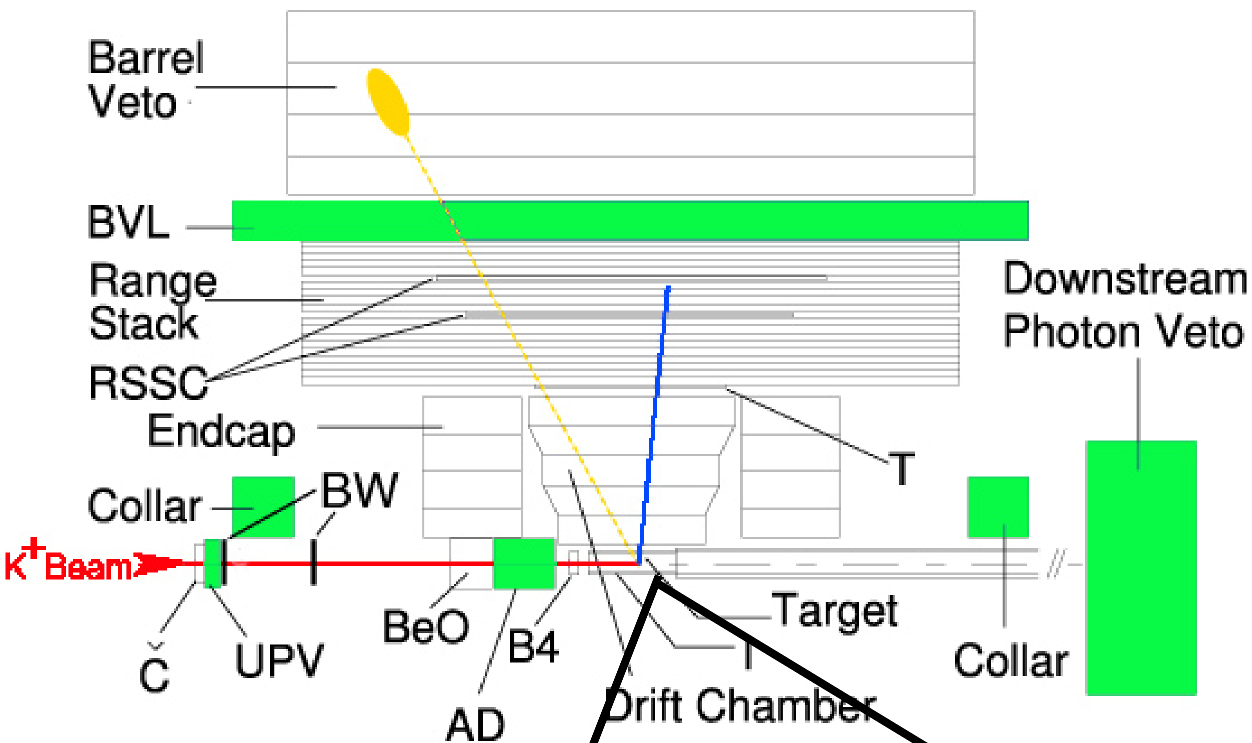
Detecting the K^+ beam



B4 Hodoscope

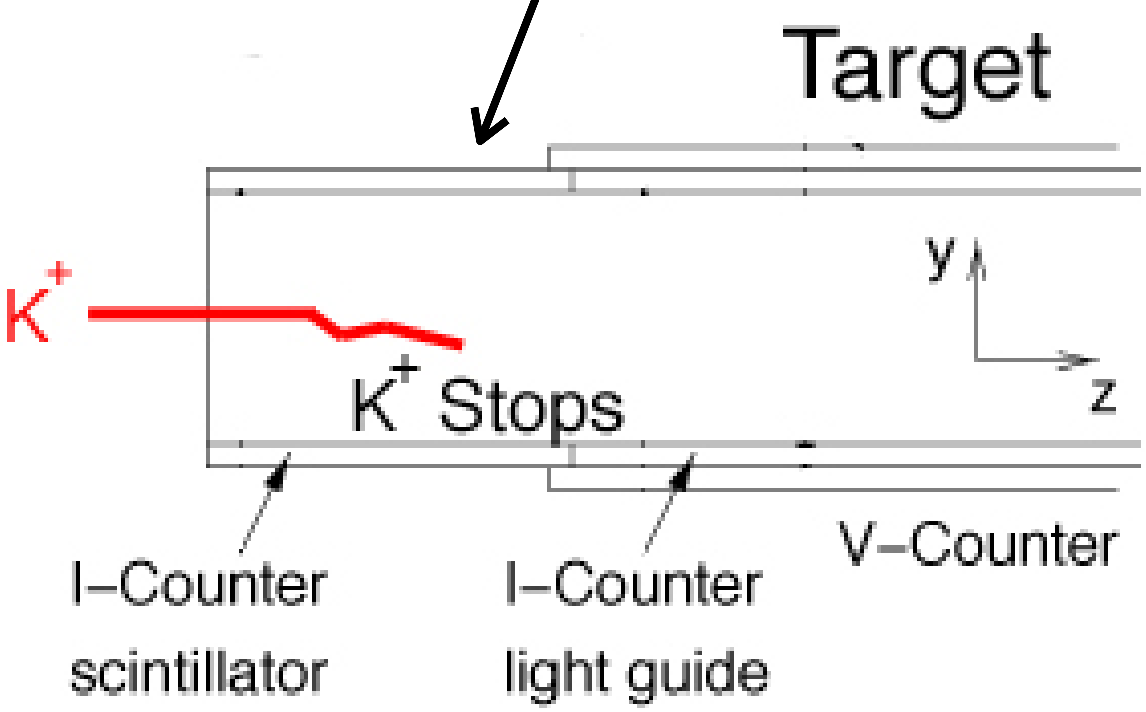
- Two orthogonal planes of scintillator "fingers"
- Good $x - y$ resolution.
- Provides information on incoming K^+ position in Target
- Particle Identification via $\frac{dE}{dX}$

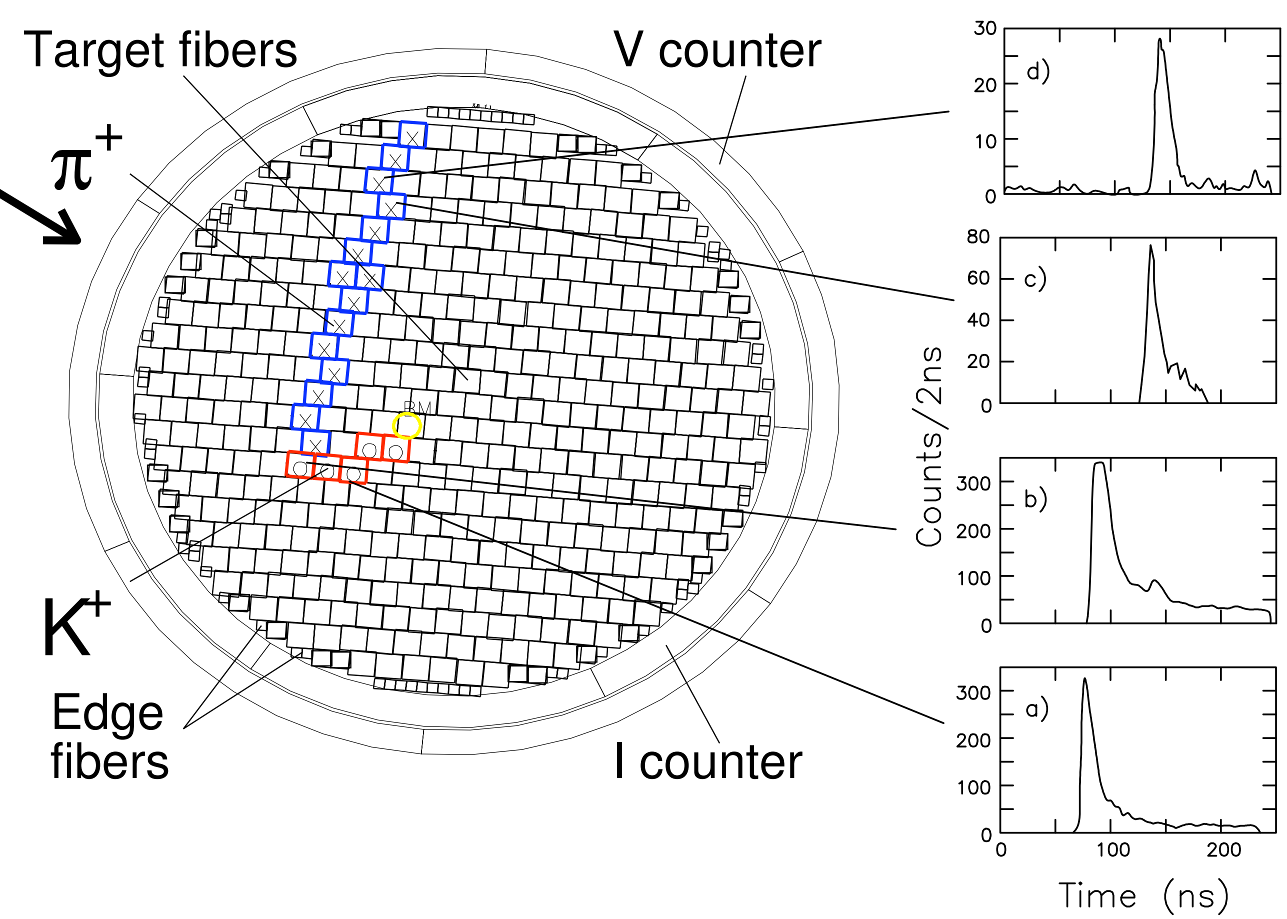
Detecting the K^+ decay



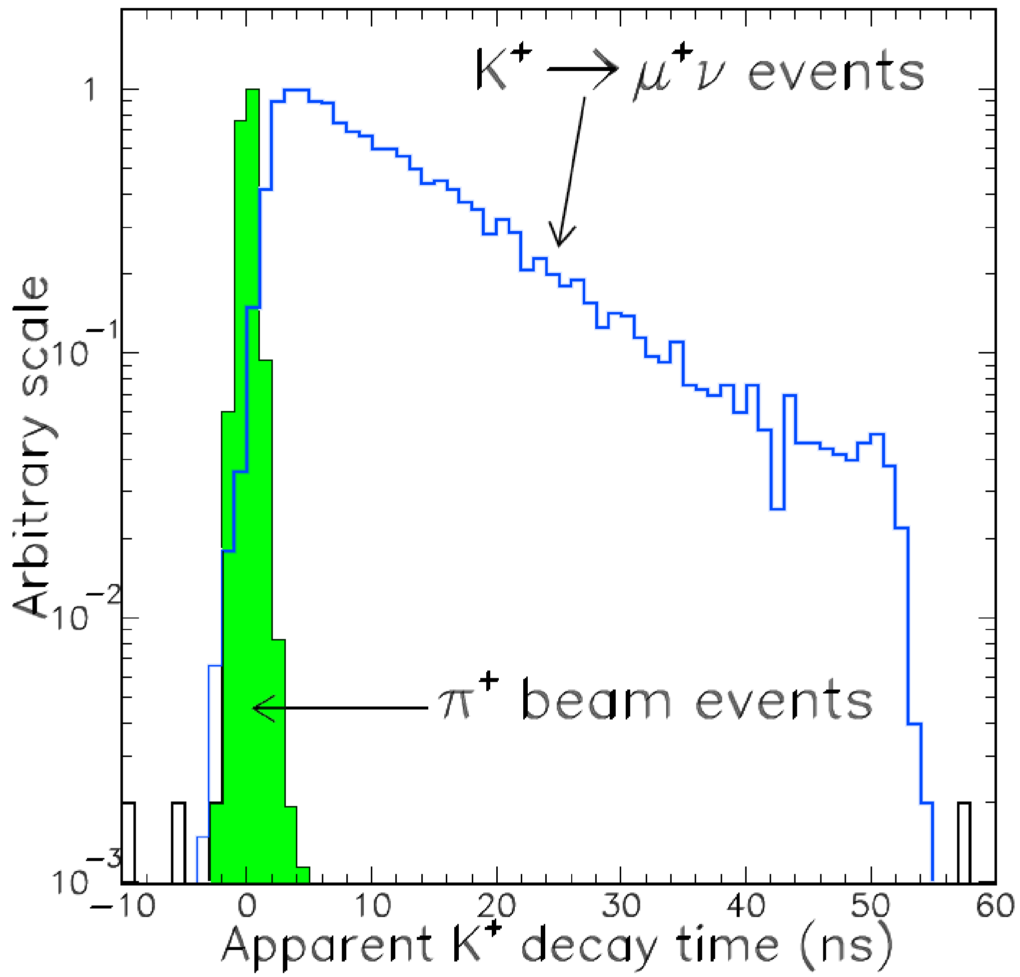
Target

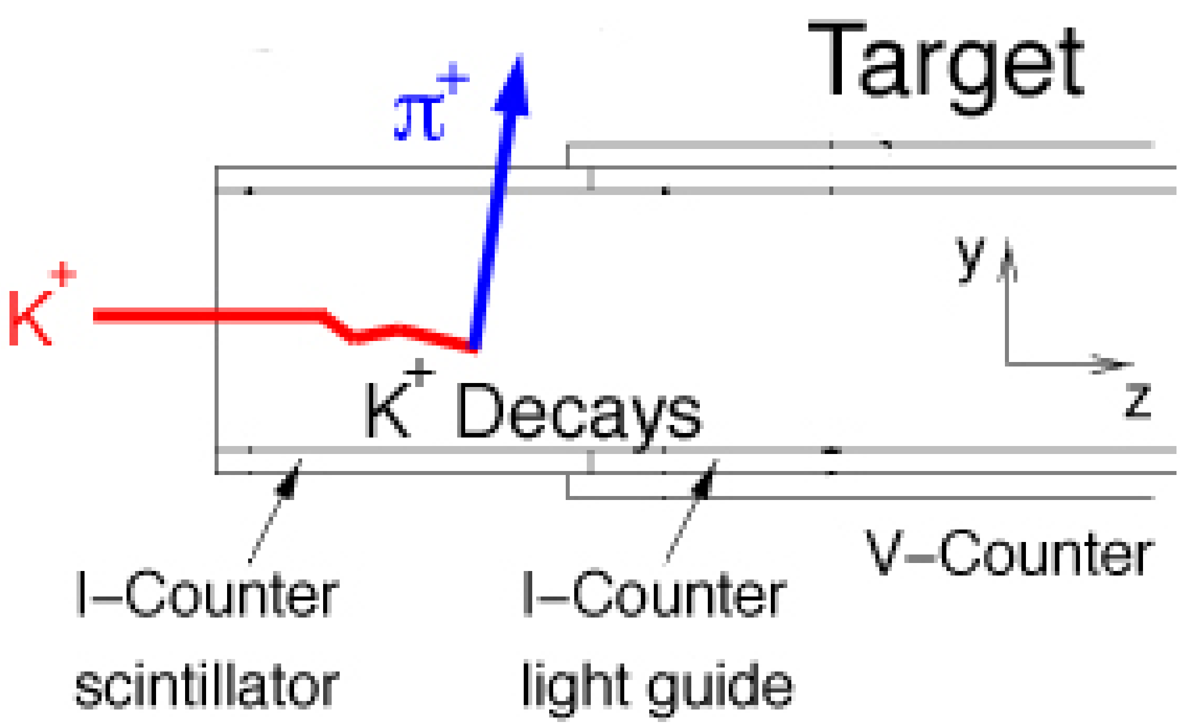
- ~ 500 scintillating fibers (0.5 mm-square)
  - Good $x - y$ resolution.
  - Poor z resolution.
- K^+ slows & stops in Target
  - Deposits $\sim 10 - 60$ MeV/$fiber$





Detecting the K^+ decay





Delayed Coincidence

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

  Time difference between

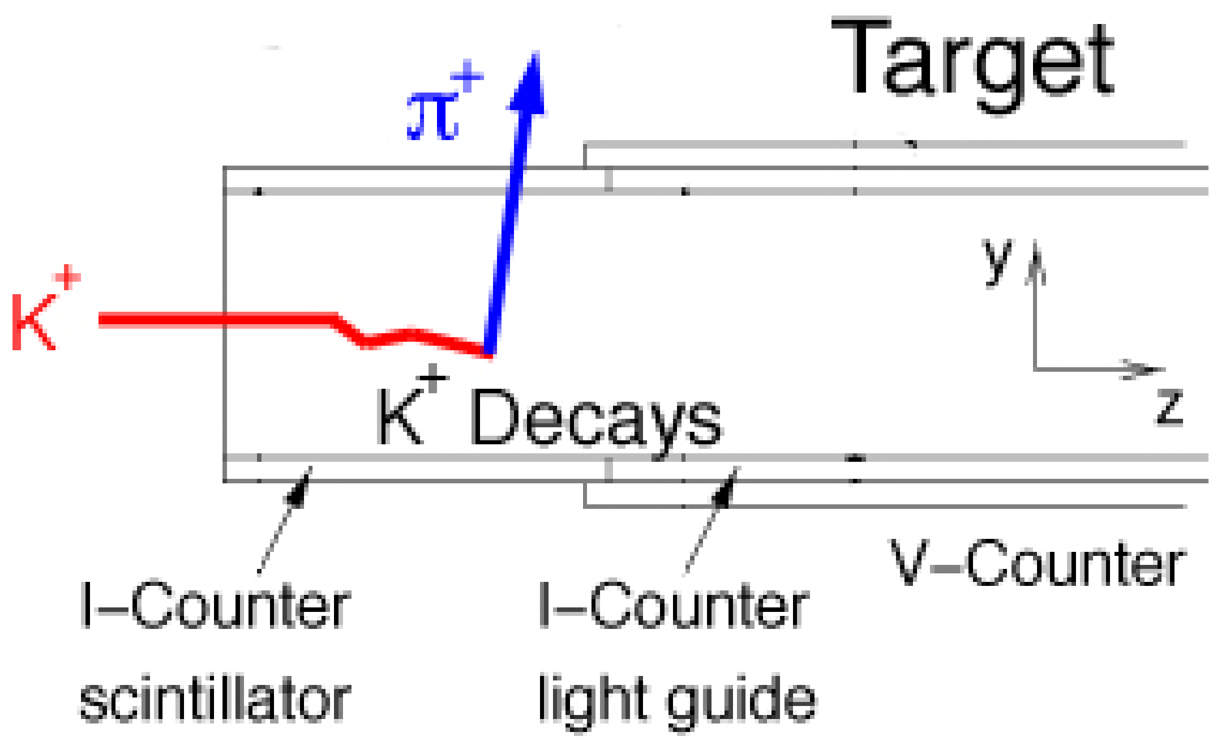
  incoming K^+ and outgoing π^+

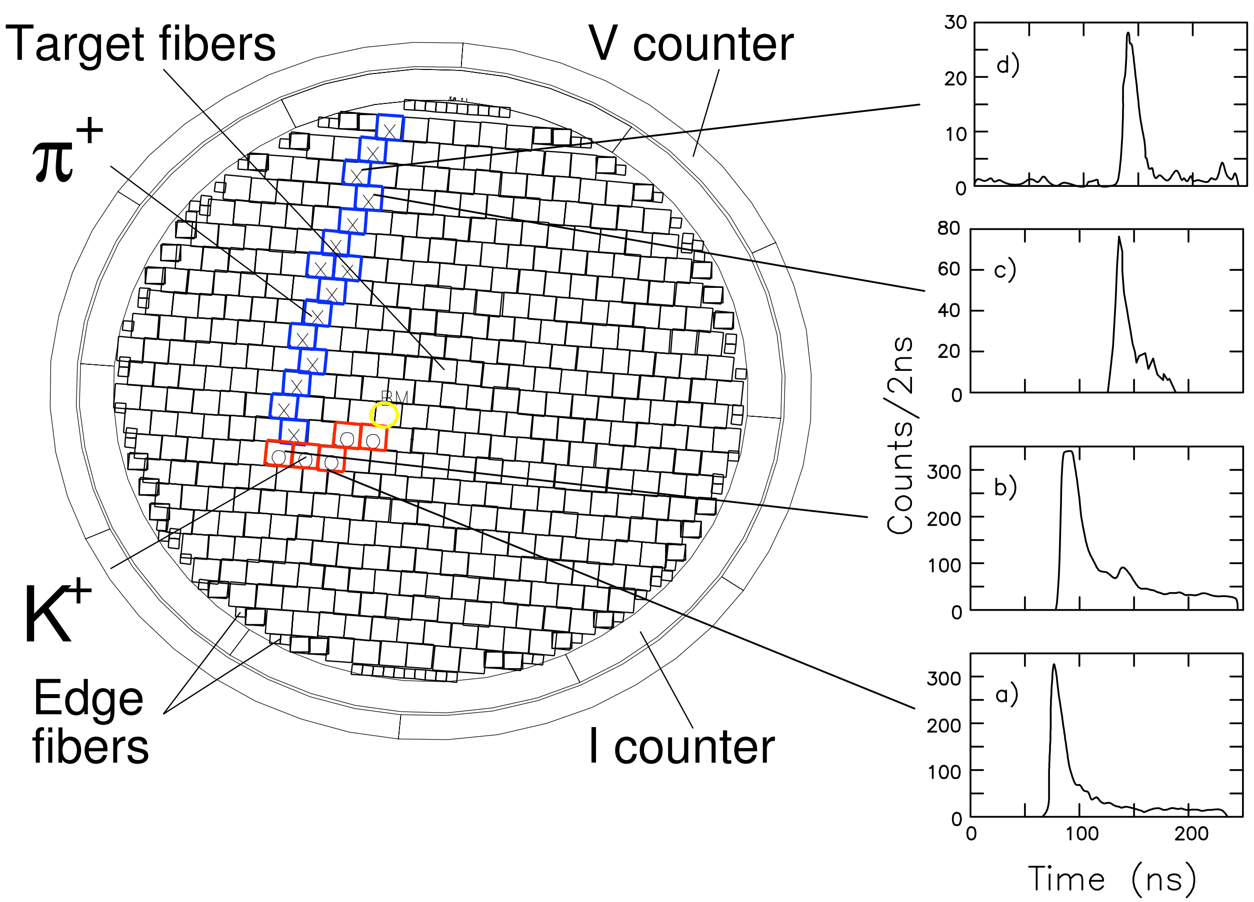
- Removes Beam Background

  Decay-in-flight background

  π^+-beam scatters

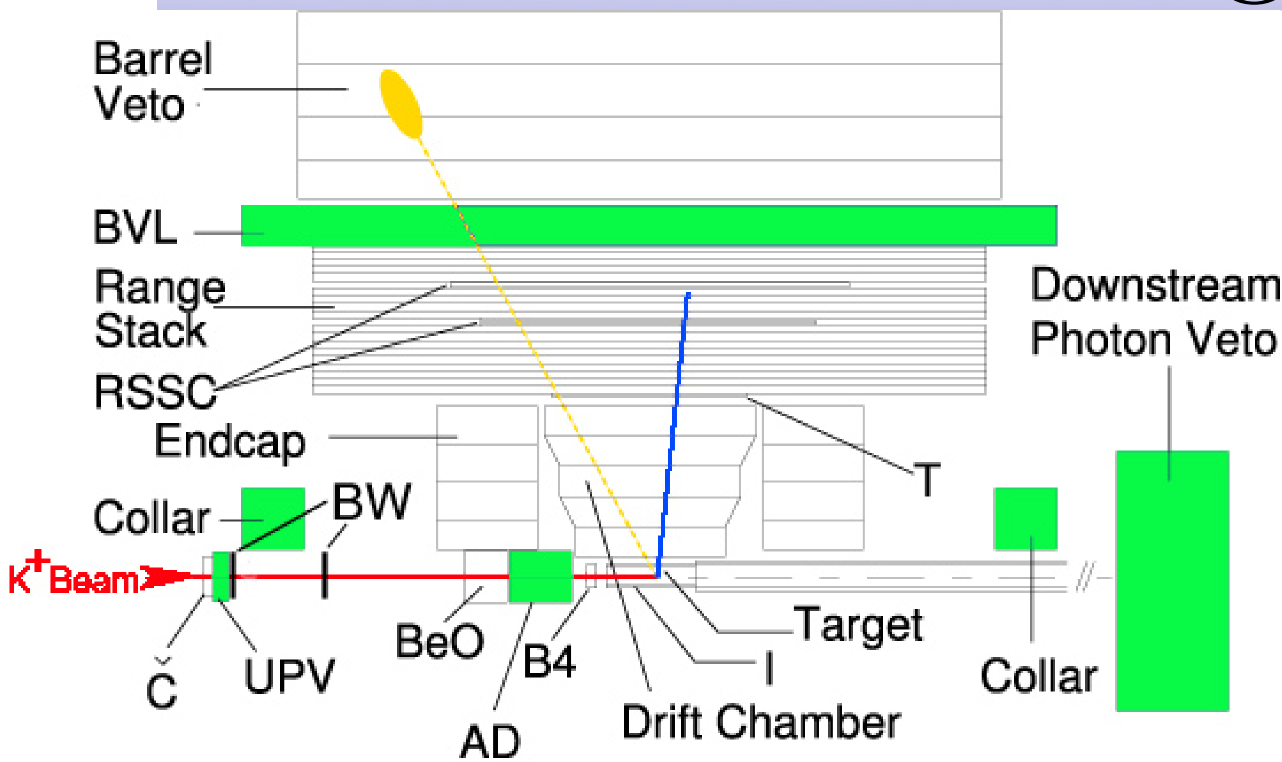
Detecting the K^+ decay



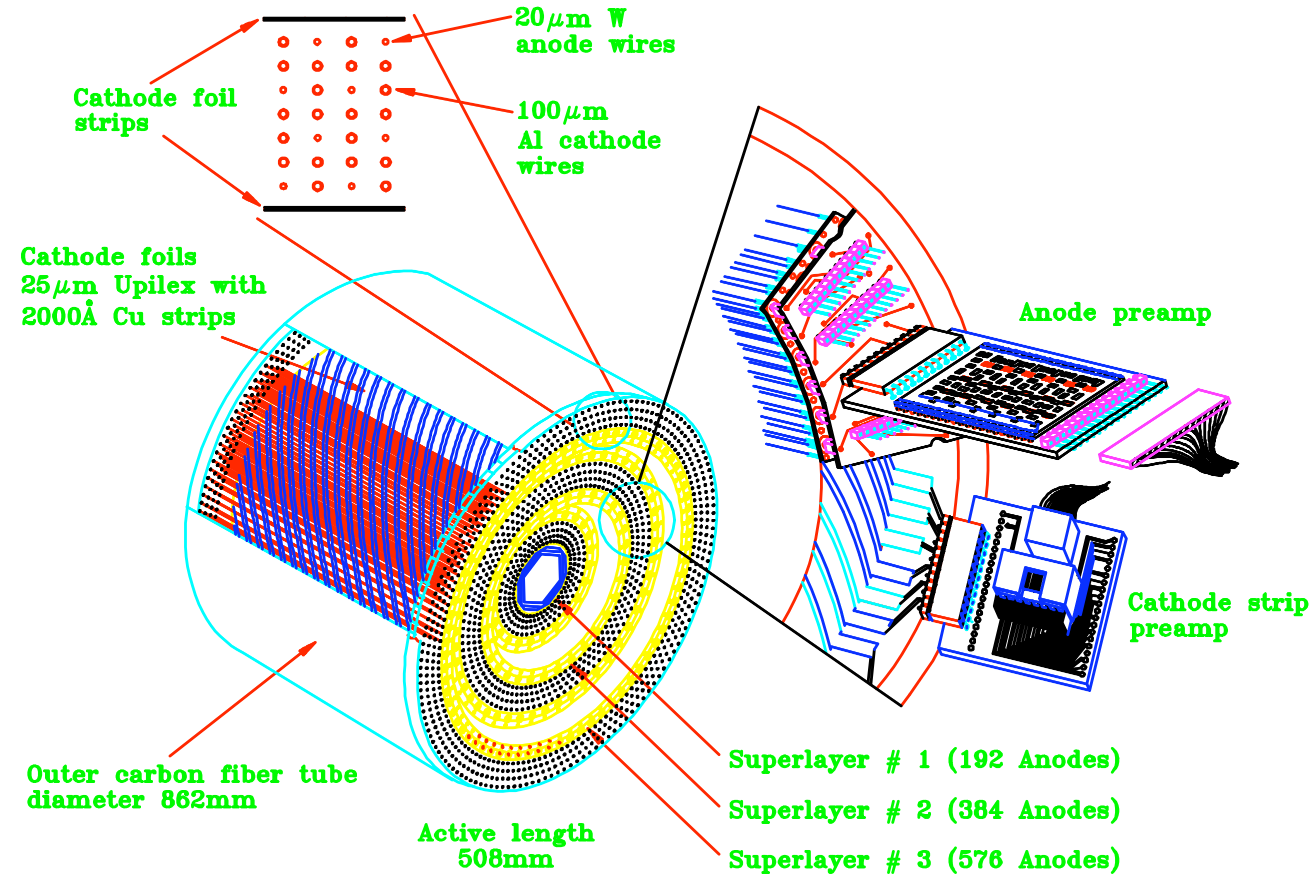


- π^+ Decays
  - Minimum ionizing particle
  - $\sim 0.1 - 1.5$ MeV$/fiber$
- I (don't know what I means)-Counter
  - Ring of scintillator, 6 segments
  - Triggers outgoing charged track
  - Defines fiducial region
- V(eto)-Counter
  - Vetoes charged tracks outside fiducial region

Detecting the π^+



UTC

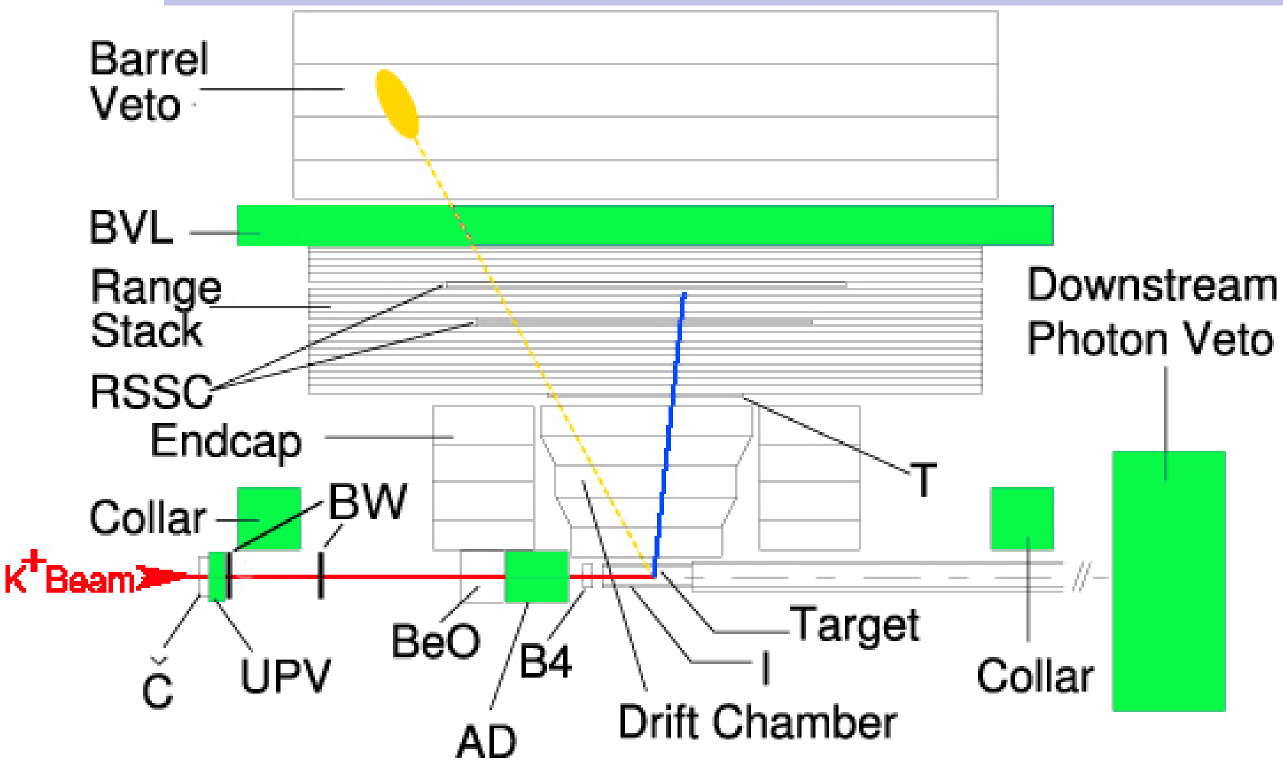


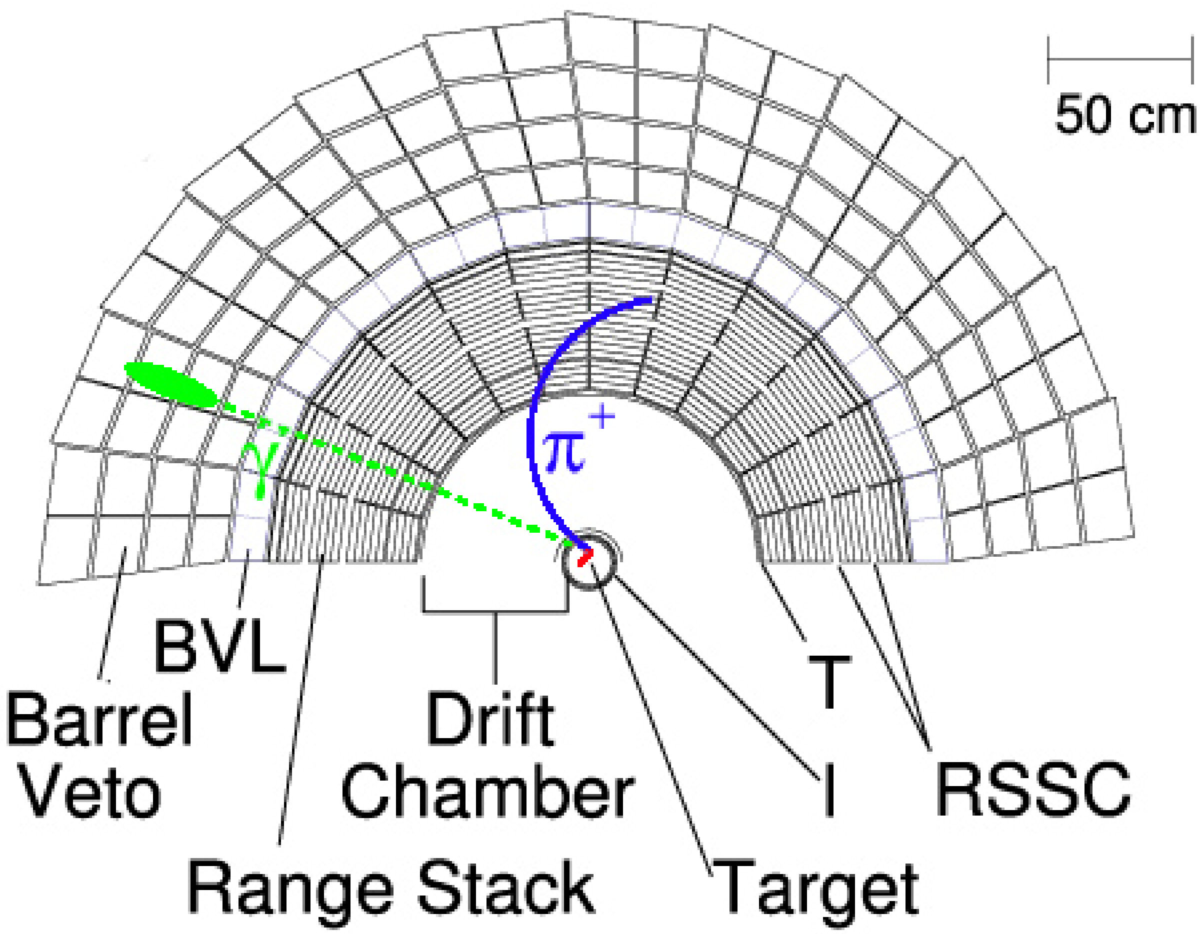
- Detects charged tracks
- ~~Very~~^{Ultra} Thin Chamber

  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^+

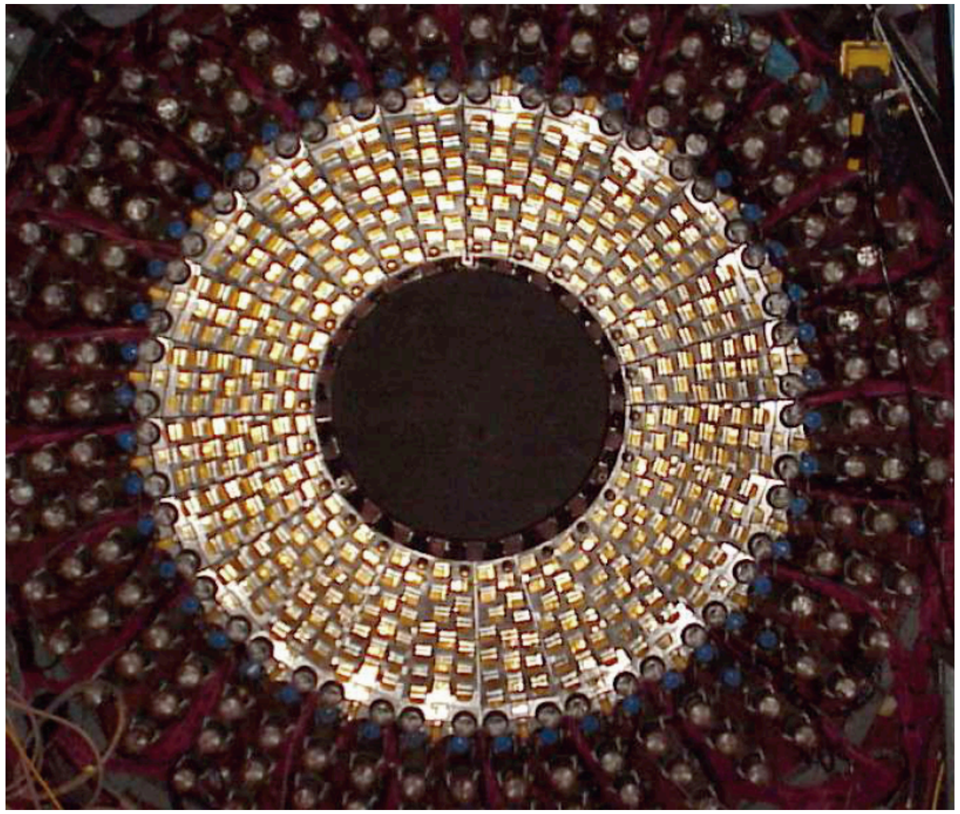




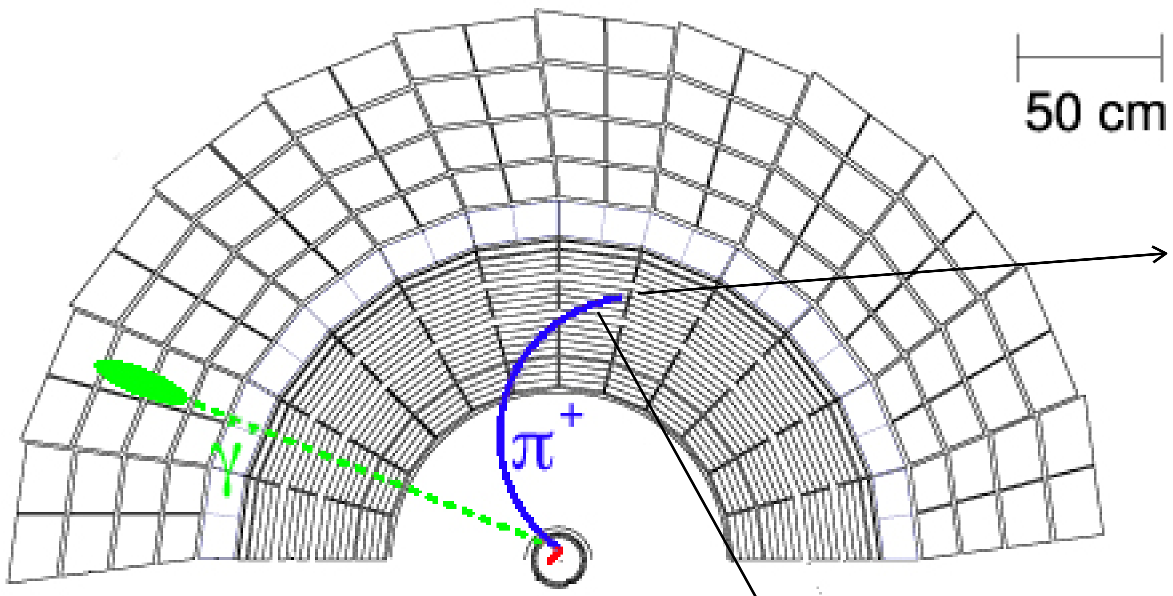
Range Stack

- 19 Layers of plastic scintillator
  - Layer 1 = T (trigger,thin)-counter (0.635 cm)
    Used as *trigger* condition
    Defines geometrical (fiducial) region
  - Layers 2-18 are 1.905 cm (3/4 in)
- Measure *Range* and *Energy* of charged track
  - Range = distance traversed by π^+ in scintillator.
- Particle ID

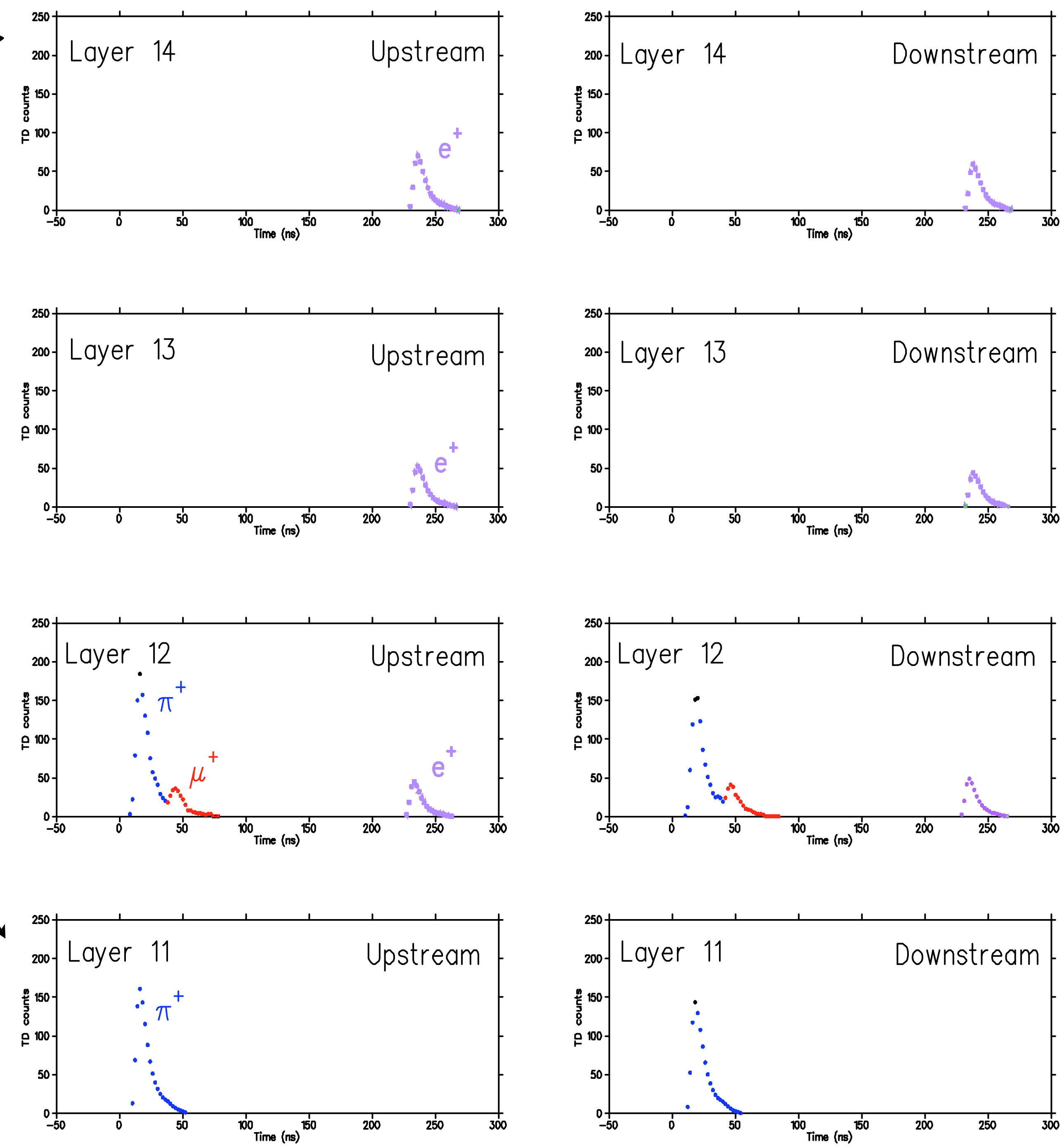
  $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\bar{\nu}_e\nu_\mu$



Identifying the π^+



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



- Sample pulse height in Range Stack

  Every 2 ns for 2 μs

  TDC's for 10 μs

- $\pi^+ \rightarrow \mu^+$

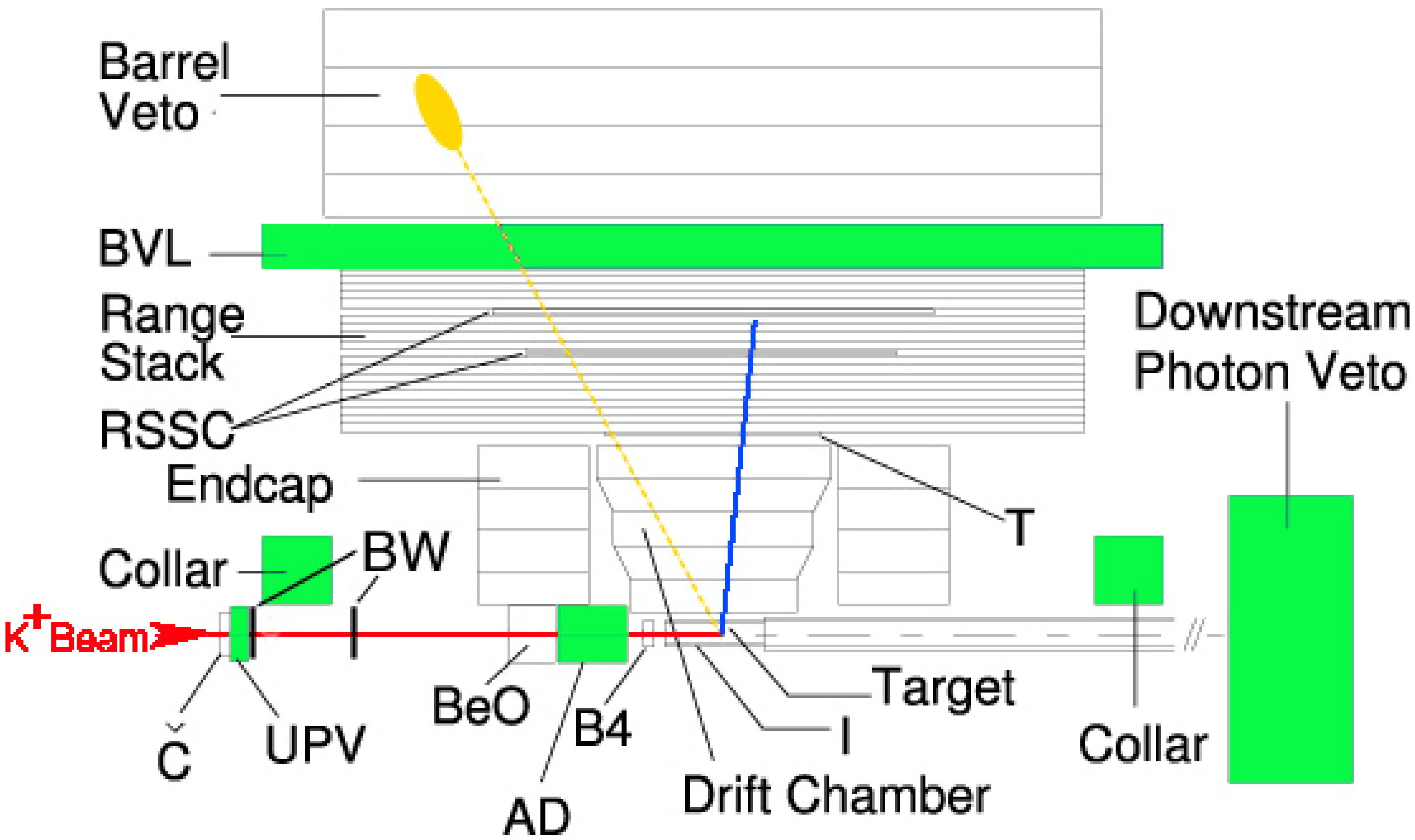
  $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm,

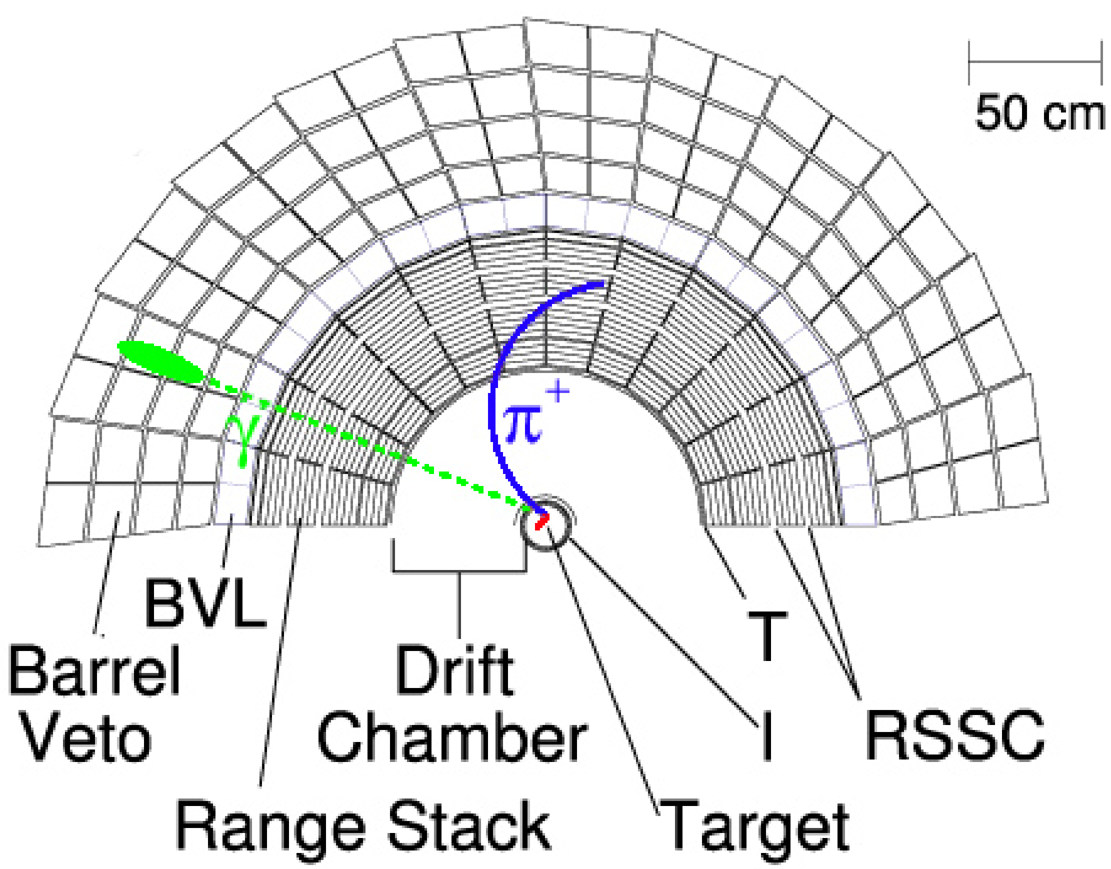
  $\tau_\pi = 26.0$ ns

- $\mu^+\nu_\mu \rightarrow e^+\bar{\nu}_e\nu_\mu$

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

Detecting Photons in Barrel Region





- Barrel Veto (BV)

  Pb-scintillator

  14.3 rad. lengths
- BV-Liner (BVL)

  Newer BV layer

  Larger solid angle

  2.3 rad. lengths
- Range Stack

  Scintillator

  0.8 rad. lengths
- Target

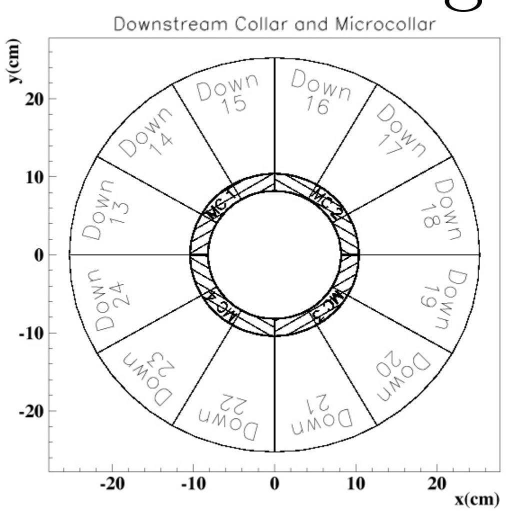
  Scintillator

  0.2 rad. lengths

Detecting Photons in Beam Region

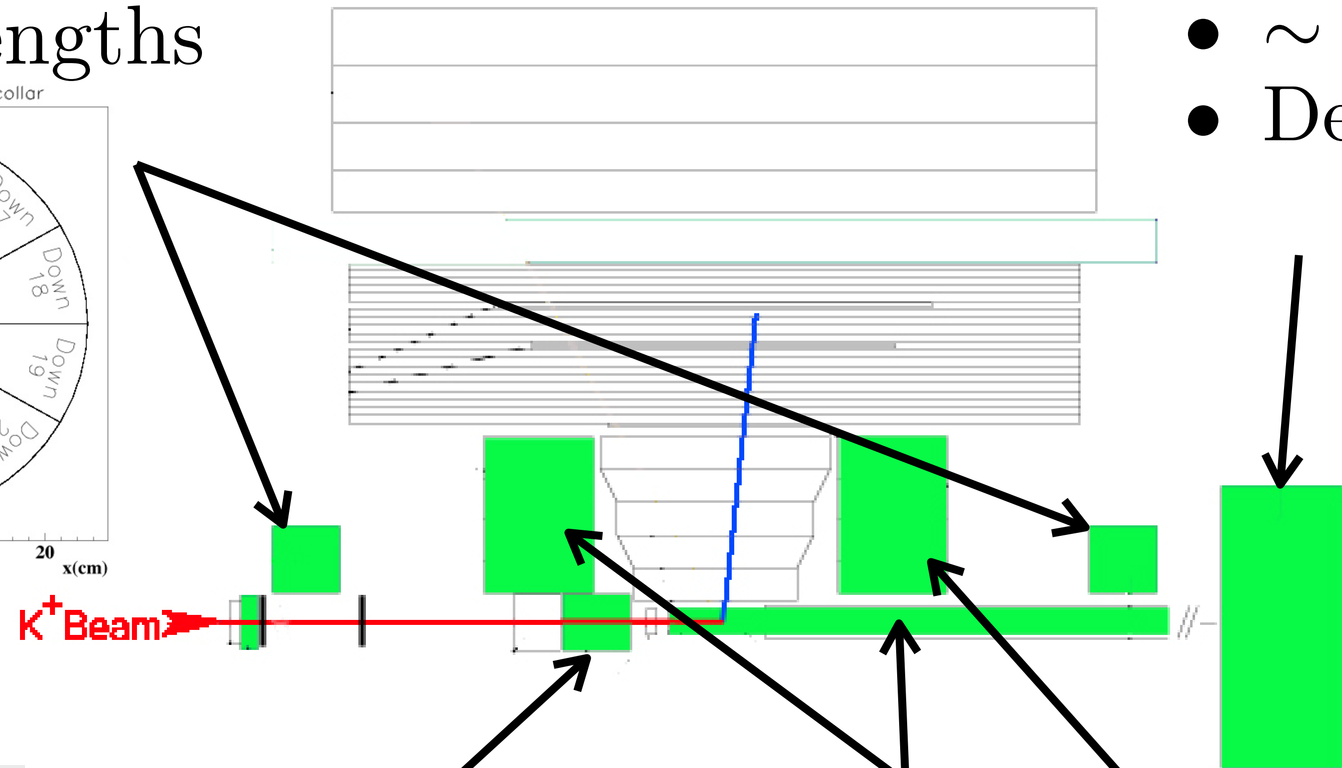
Collars

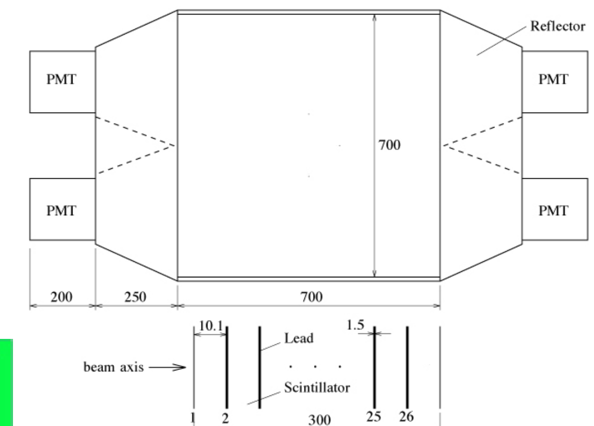
- Lead/Scintillator sandwich
- 9 rad. lengths

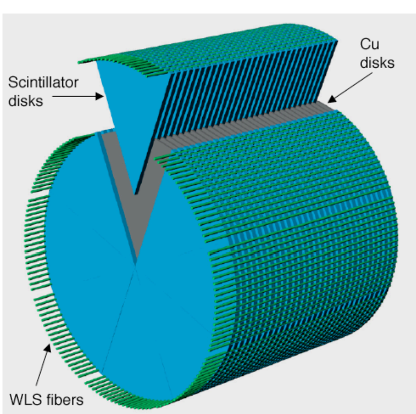


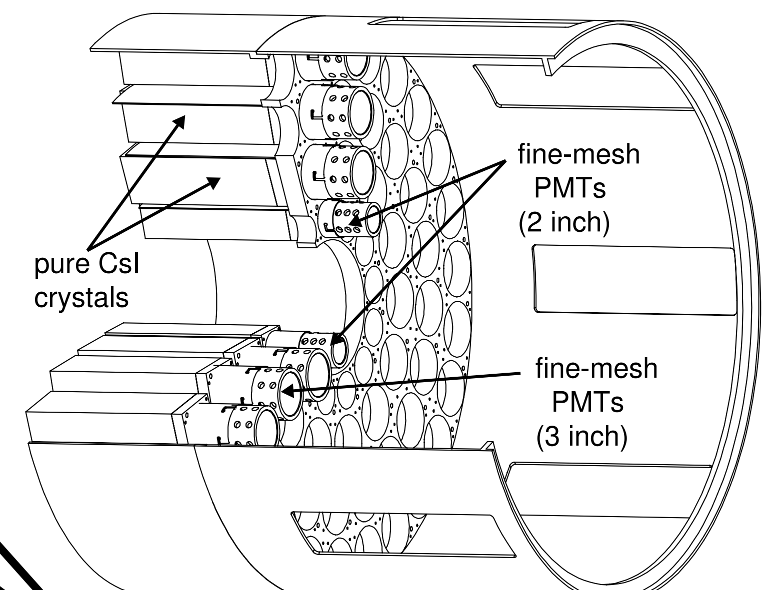
Downstream PV

- Lead/Scintillator sandwich
- ~ 7 rad. lengths
- Detects downstream traveling









Active Degrader

- Copper & Scintillator
- ~ 6 rad. lengths
- Detects upstream traveling γ

Target

- 3.1m scint. fibers
- ~ 6 rad. lengths
- Detects downstream traveling γ

End Caps

- CsI crystals
- 13.5 rad. lengths

Analysis Strategy

- *A priori* background identification.
- "Blind Analysis" never inspect signal region until backgrounds are verified.
- 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.
- Measuring Backgrounds:

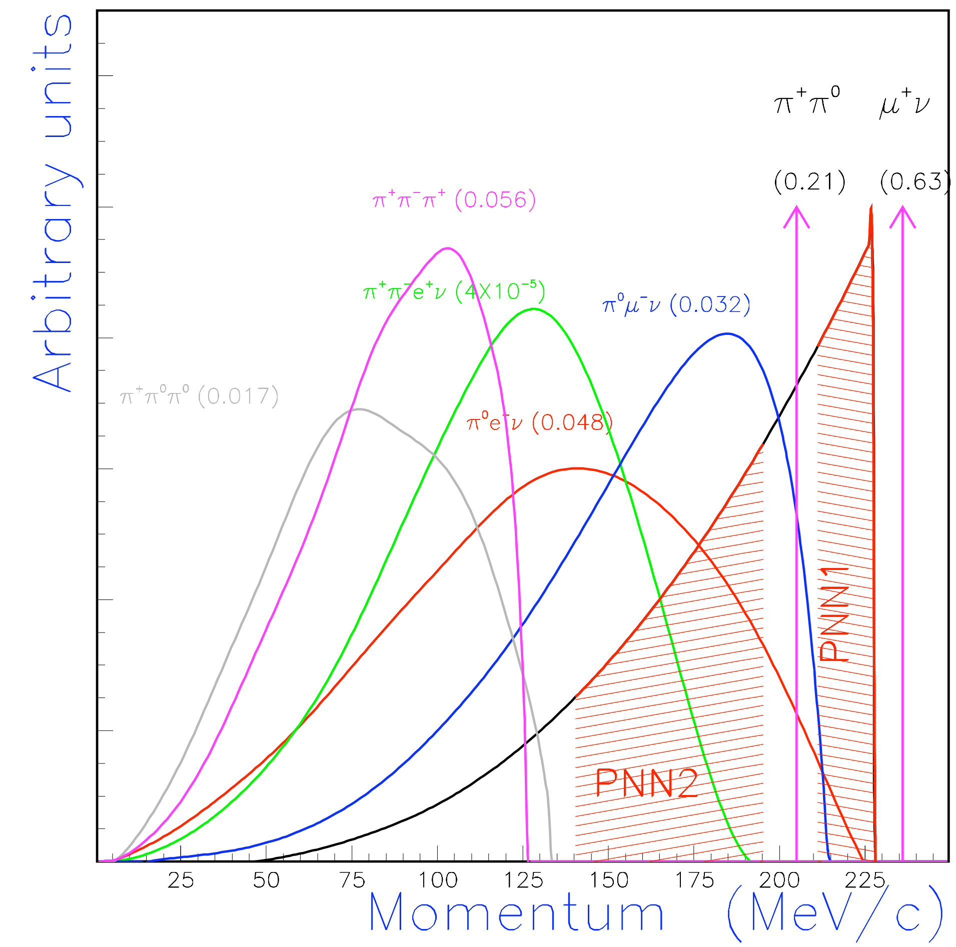
  - Simulation of detector difficult at $\mathcal{B} \sim 10^{-10}$.

  $\Rightarrow$ Use data whenever possible.

  - Loosen and tighten cut to compare to predicted rates.

A priori background identification

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



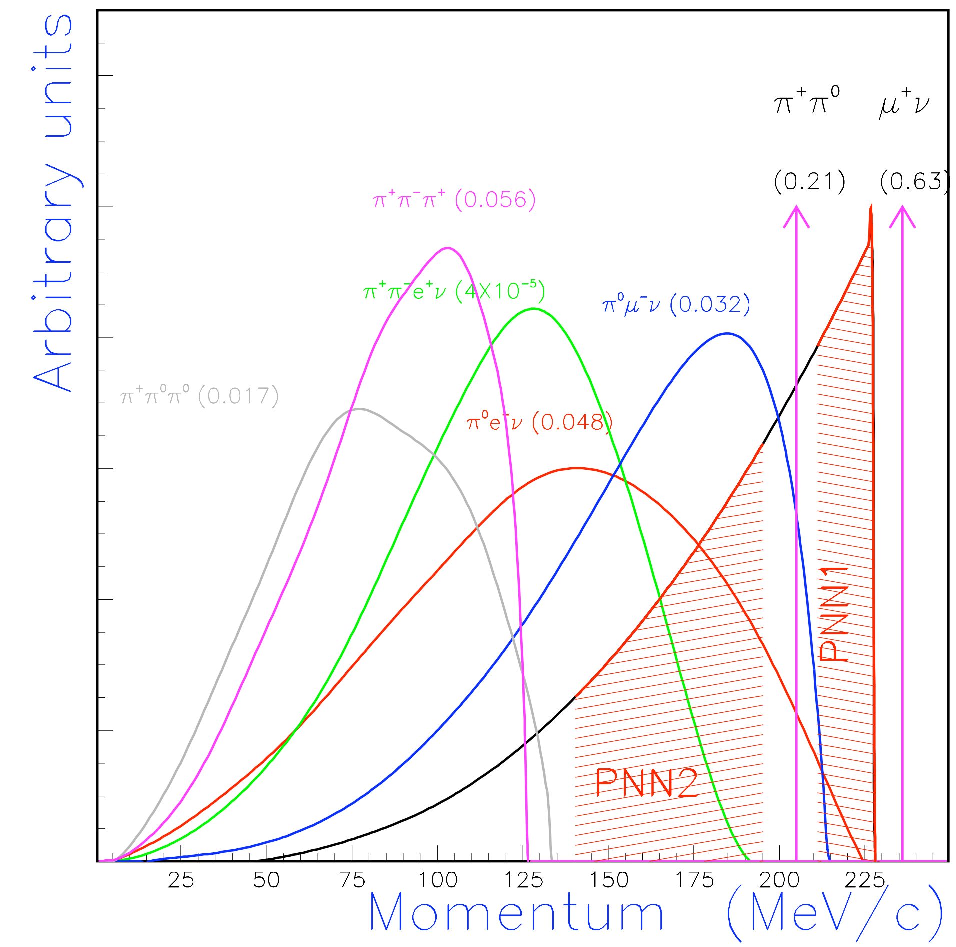
- Goal: Suppress possible backgrounds to less than the rate of $K^+ \to \pi^+\nu\bar{\nu}$

A priori background identification

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

Background Suppression →

↑ Not a background



Suppression of possible backgrounds.

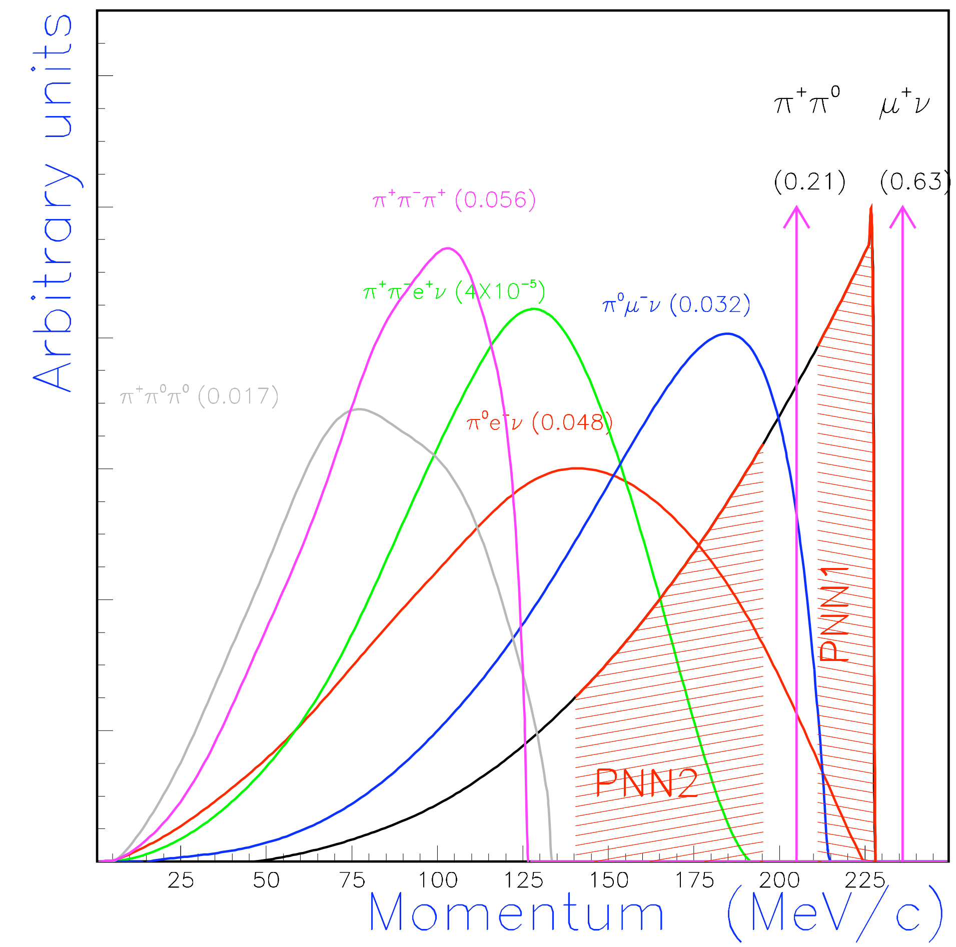
- Apply Kinematic cuts.

A priori background identification

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

Background Suppression →→

Not a background ↑



Suppression of possible backgrounds.

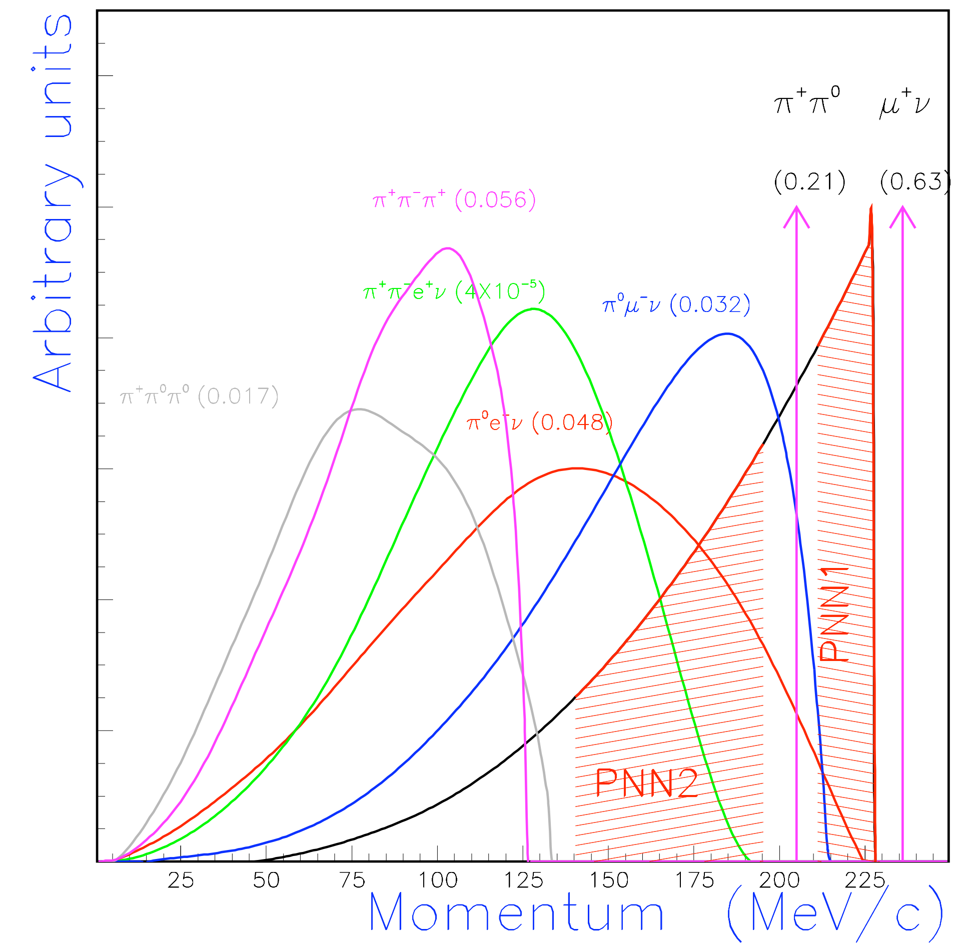
- Apply Kinematic cuts.
- Apply Particle ID.

A priori background identification

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

Background Suppression →→→

Not a background



Suppression of possible backgrounds.

- Apply Kinematic cuts.
- Apply Particle ID.
- Apply Photon cuts.

A priori background identification

Process	Branching Ratio	**Kinematics** Track	**Kinematics** Extra Energy	**Delayed Coincid-ence**	**Particle ID** Track	**Particle ID** Beam	Photons Fid.	Photons Beam
Charge-Exchange Process								
$K^+n \rightarrow K^0p$	0.000028							
$K_L^0 \rightarrow \pi^+\mu^-\bar{\nu}$	0.1350		$\checkmark$	$\checkmark$				
$K_L^0 \rightarrow \pi^+e^-\bar{\nu}$	0.1940		$\checkmark$	$\checkmark$				
Backgrounds from Beam								
π-Beam	-			$\checkmark$		$\checkmark$		
K-DIF	-			$\checkmark$	$\checkmark^{*}$	$\checkmark$	$\checkmark^{*}$	
KK-Beam	-		$\checkmark$		$\checkmark^{*}$	$\checkmark$	$\checkmark^{*}$	
Kπ-Beam	-		$\checkmark$			$\checkmark$		
Charged-track scatter in Target								
$K^+ \rightarrow \mu^+\nu$	0.6344				$\checkmark$			
$K^+ \rightarrow \pi^+\pi^0$	0.2092		$\checkmark$					$\checkmark^{2}$
$K^+ \rightarrow \pi^+\pi^0\gamma$	0.000275		$\checkmark$				$\checkmark$	$\checkmark^{2}$
Charged-track scatter in Range Stack								
$K^+ \rightarrow \mu^+\nu$	0.6344	$\checkmark^{P}$			$\checkmark$			
$K^+ \rightarrow \pi^+\pi^0$	0.2092	$\checkmark^{P}$	$\checkmark$				$\checkmark^{2}$	
$K^+ \rightarrow \pi^+\pi^0\gamma$	0.000275		$\checkmark$				$\checkmark^{3}$	

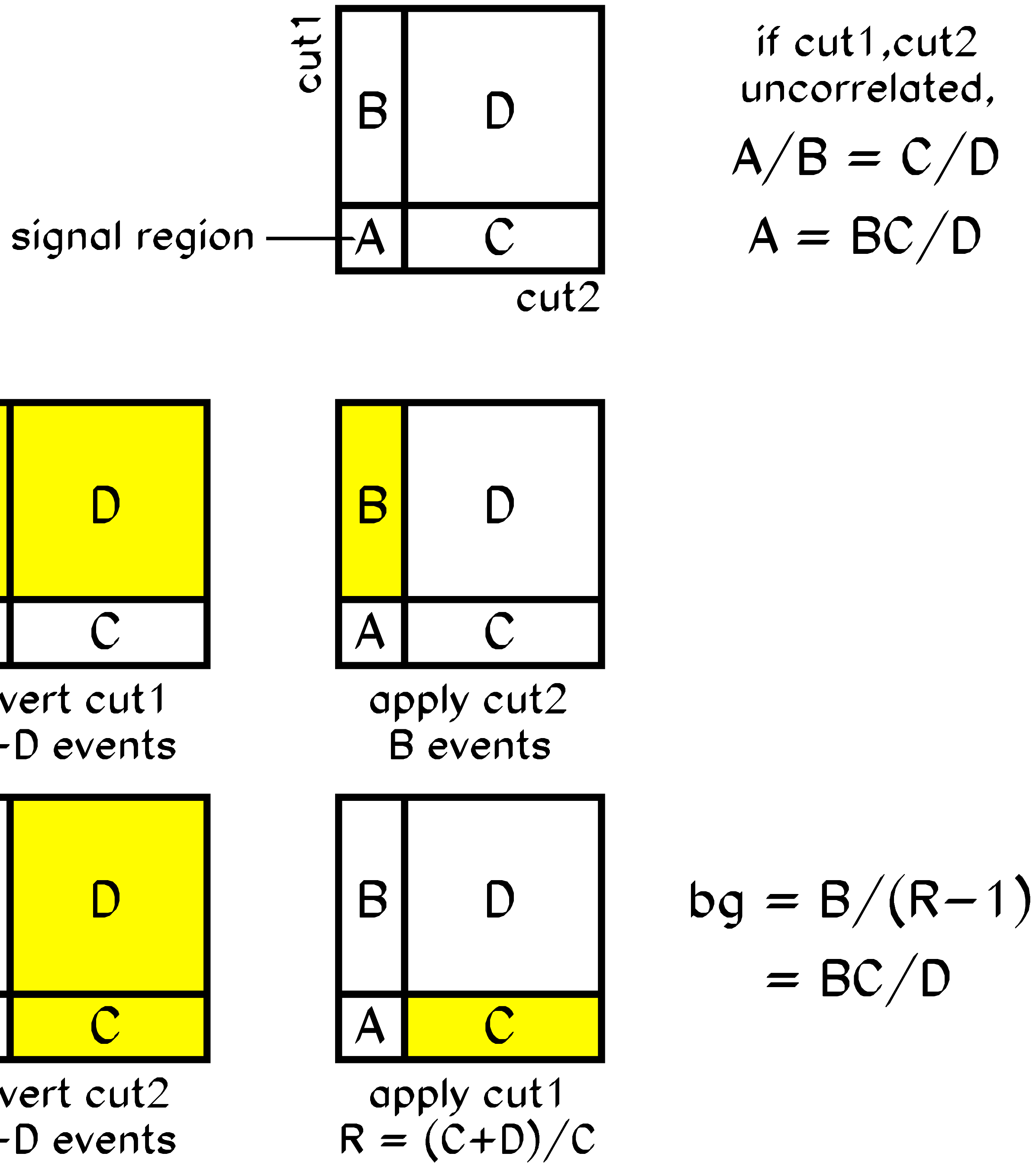
Background Suppression →→→→

↑ Not a background

Suppression of possible backgrounds.

- Apply Kinematic cuts.
- Apply Particle ID.
- Apply Photon cuts.
- Apply Delayed Coincidence.

Background Estimation using Bifurcation Method



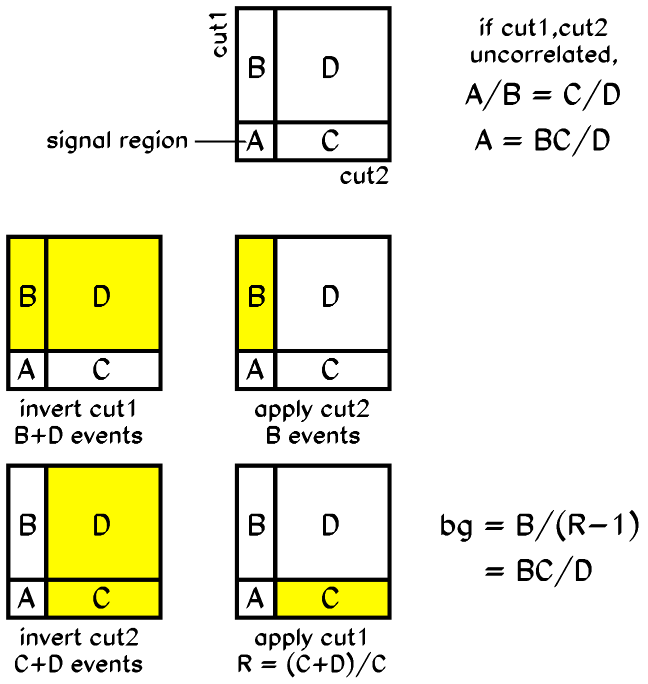
- Signal Region (A) always blinded.

  until the end.

- Cuts must be uncorrelated.

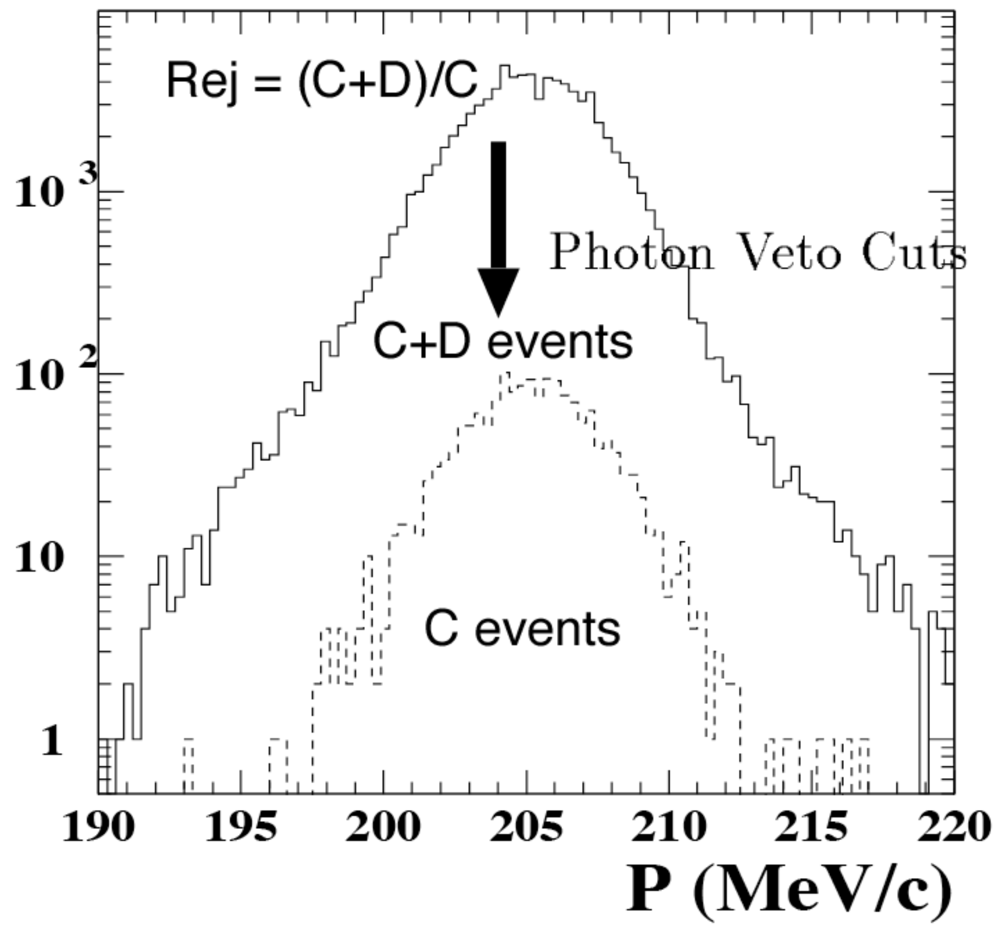
  such as PID & Kinematics

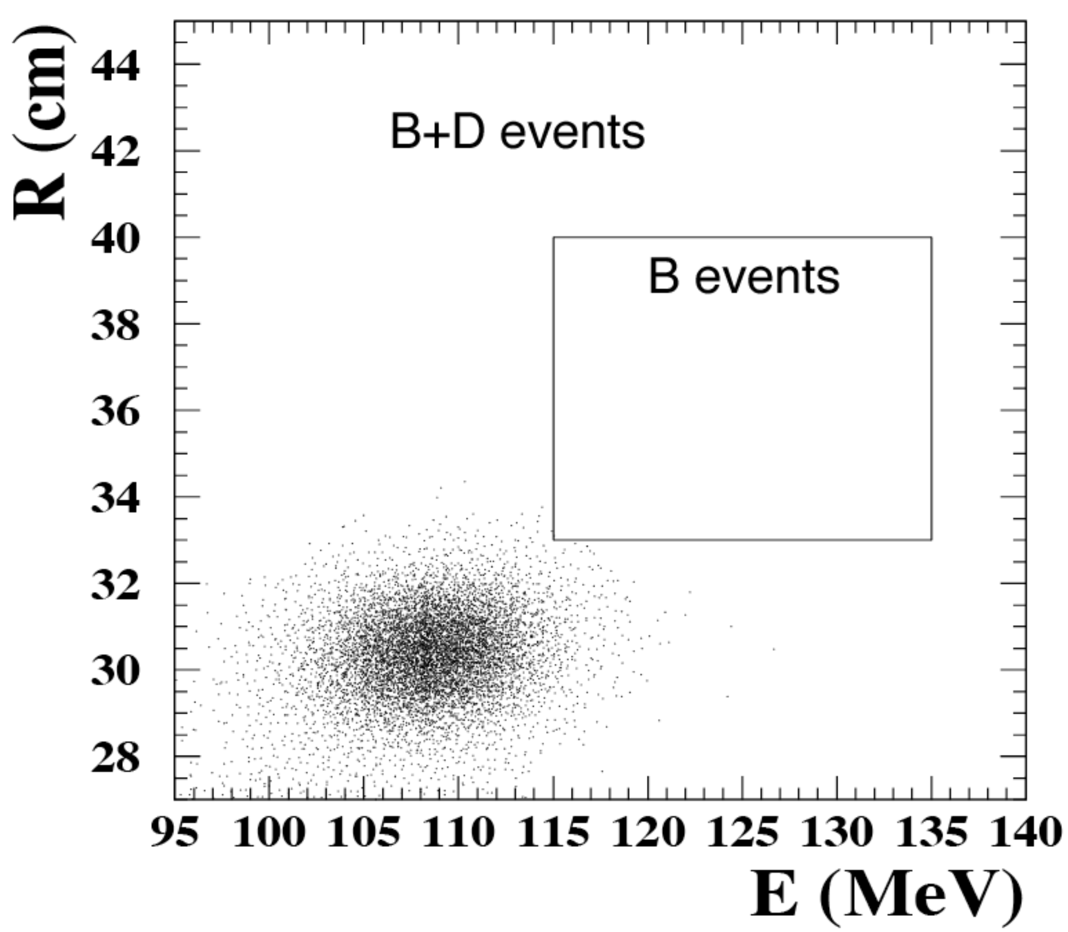
Background Estimation using Bifurcation Method



$K^+ \to \pi^+\pi^0$ 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).
  - $Background = \frac{B}{R-1}$.





Background due to Kp2 scatter in the Target

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

- π^0 direction correlated to π^+ direction before scatter

  Not so after scatter.

- Rejection of photons along beam direction differs from fiducial region (Barrel-Veto, Range Stack).

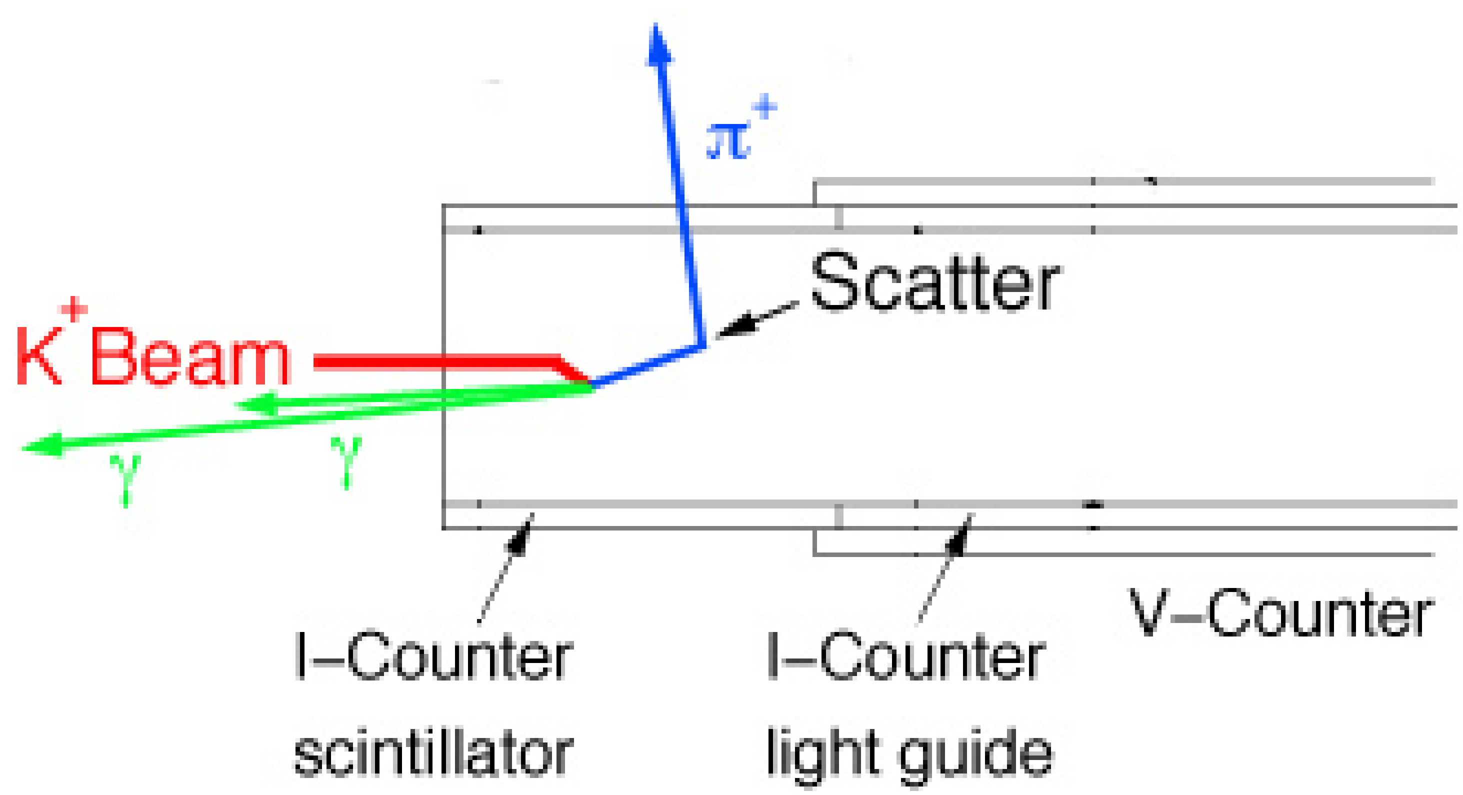
  - γ's from π^0 directed toward weak photon coverage

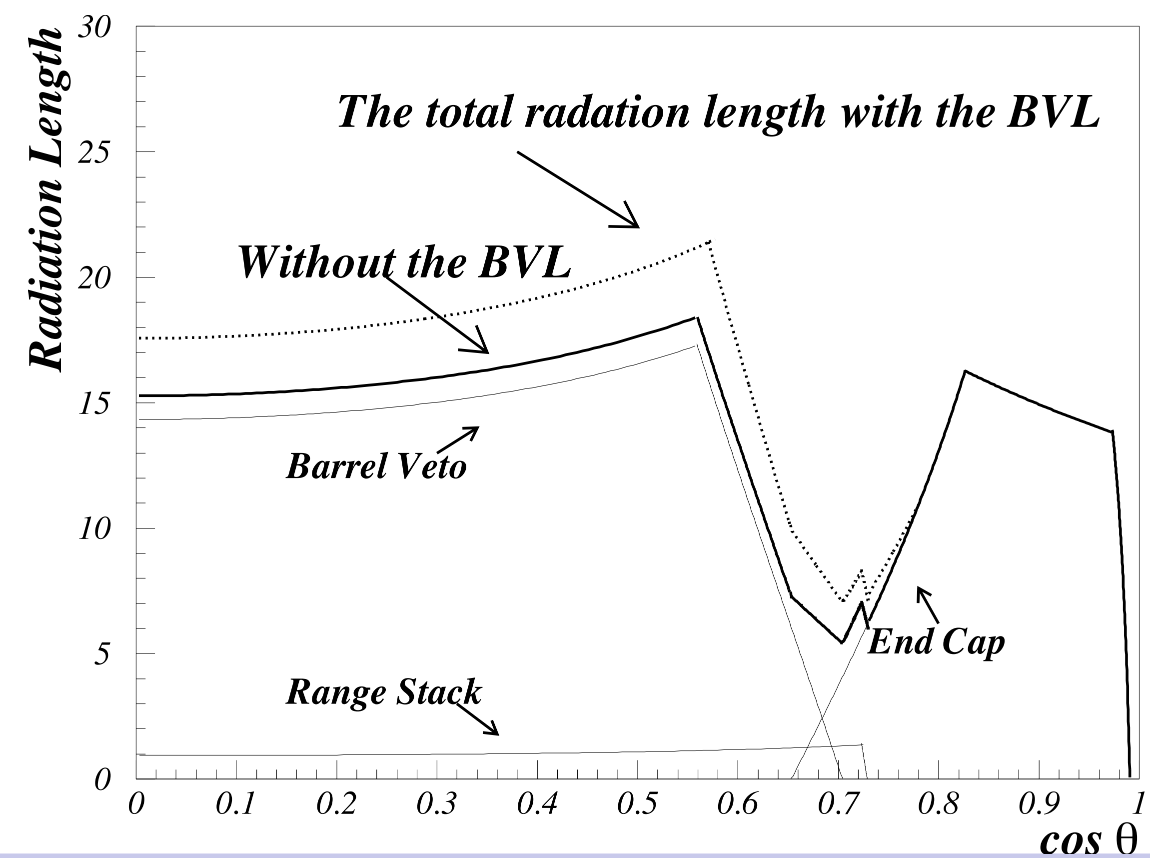
    for target-scattered event.

- π^+ from $K_{\pi 2}$ @ 205 MeV/c may now be in PNN2 signal region.

  $\Rightarrow$ Unable to 'tag' with kinematics to measure

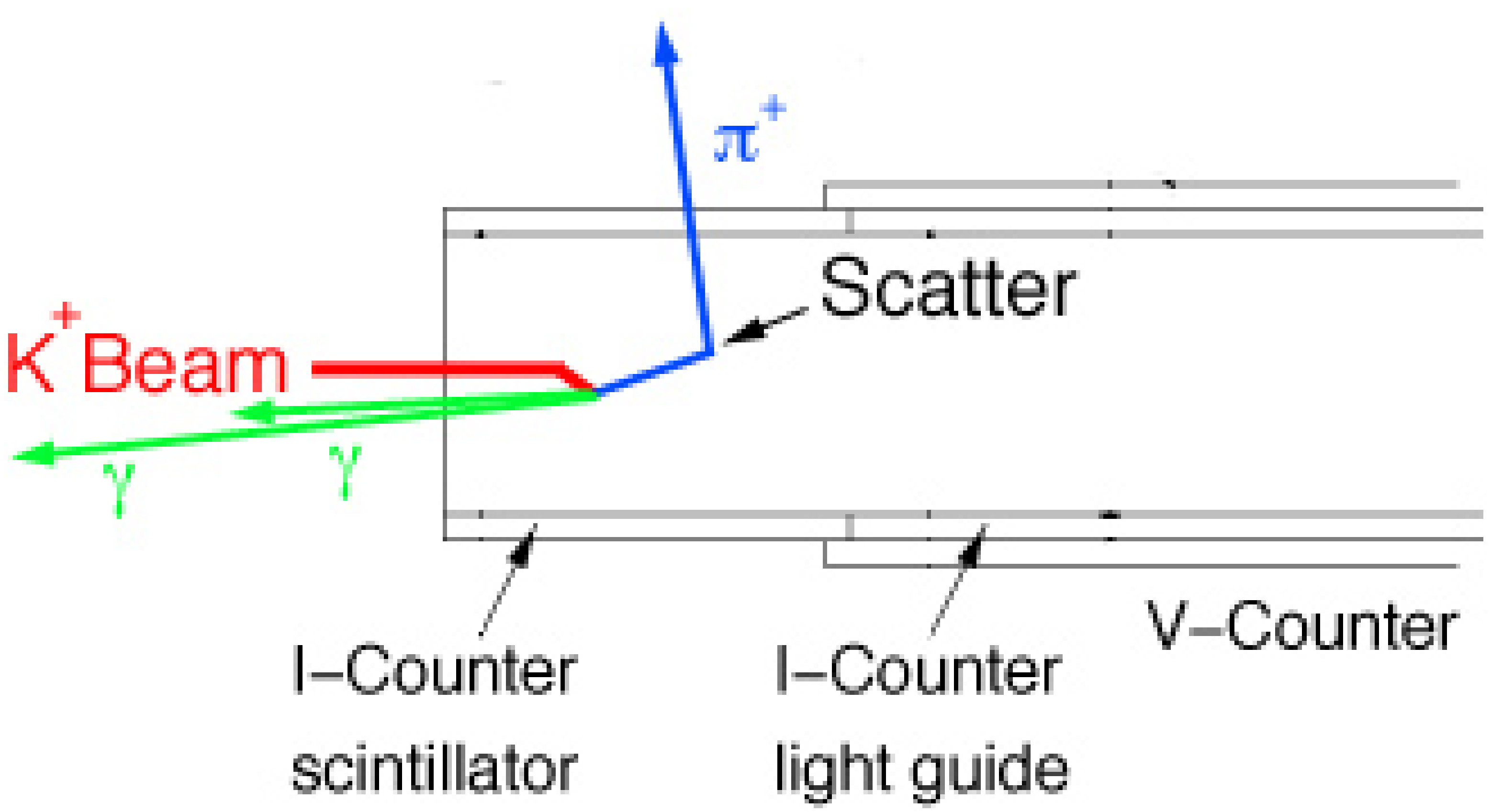
  photon-veto rejection.

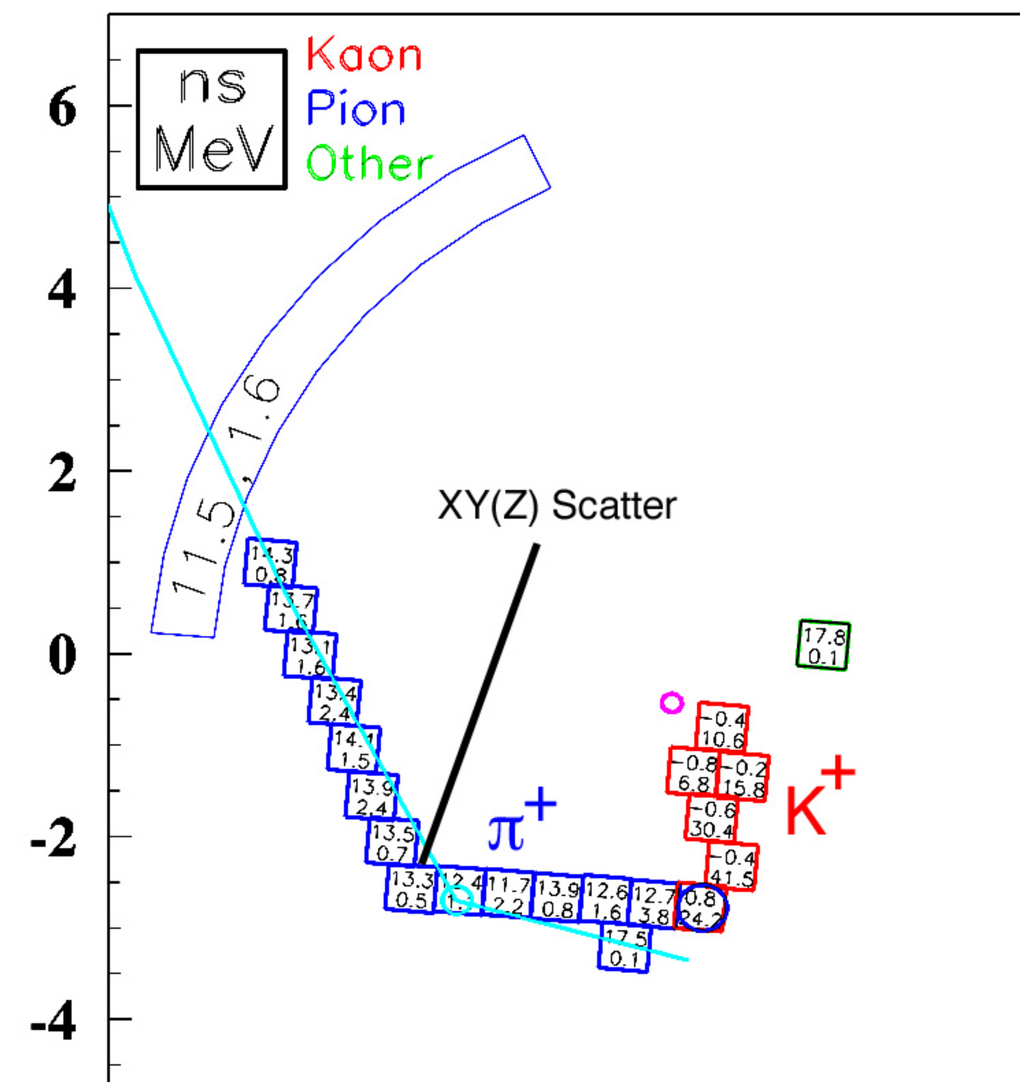




Mastering the $K_{\pi2}$-scatter Background

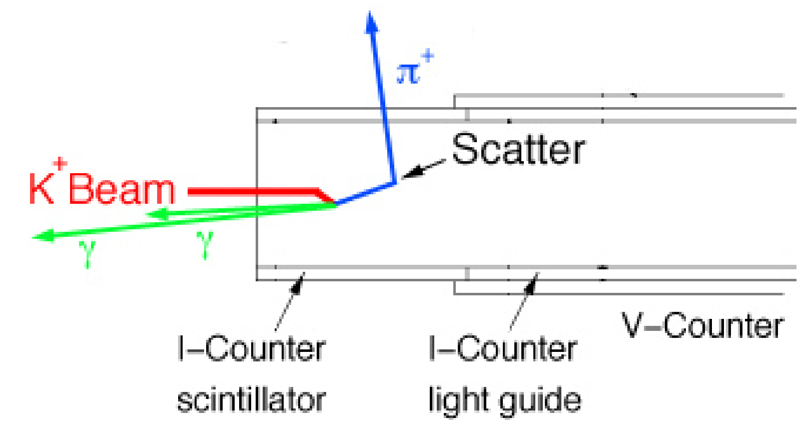
- What is a "kink"?
  - Scattering in the $x - y$ (and sometimes z) direction.
- Identifying a kink:
  - Pattern recognition of a bend in the outgoing charged track from the Target.
- Use this sample for understanding rejection of photons along beam direction (z-axis).

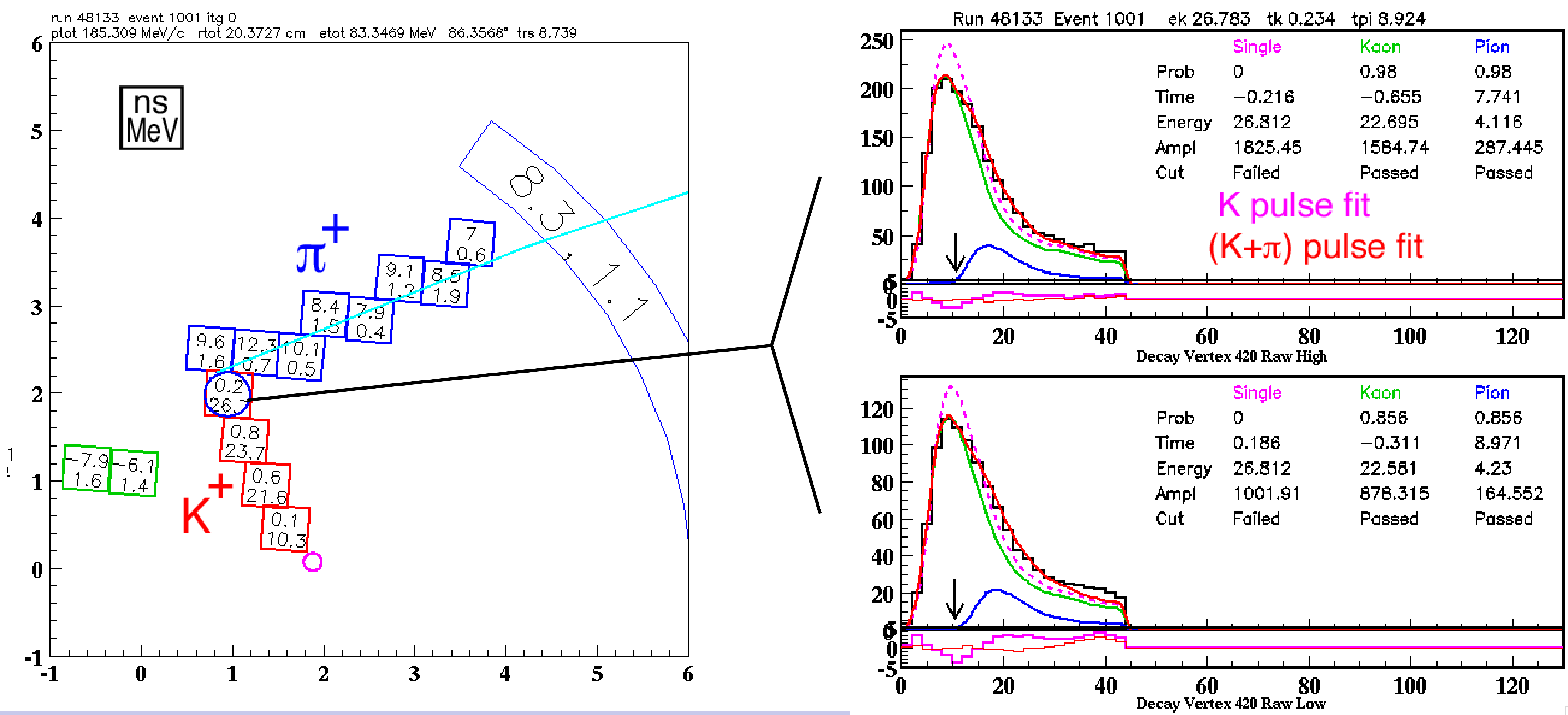




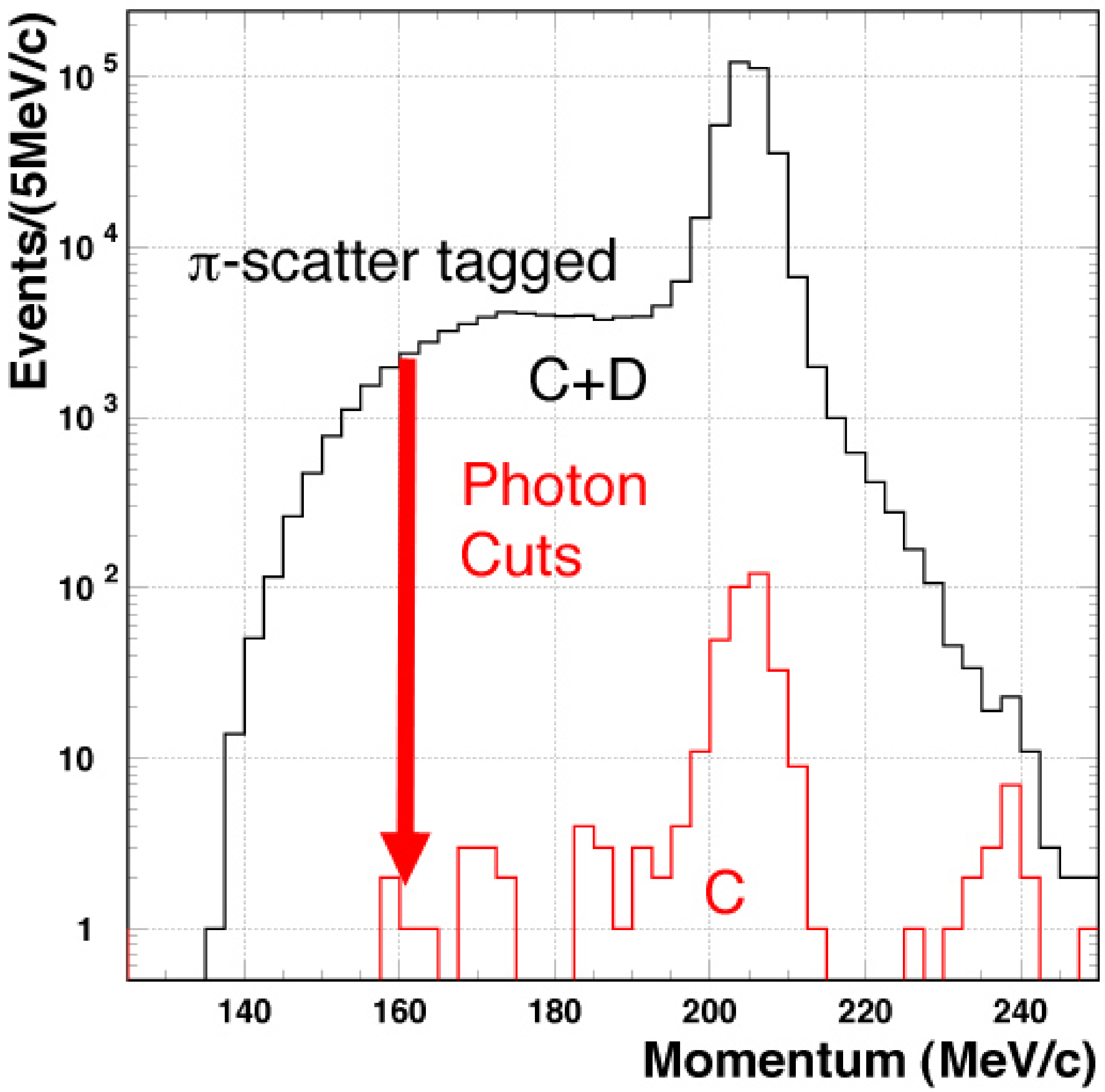
Mastering the $K_{\pi 2}$-scatter Background

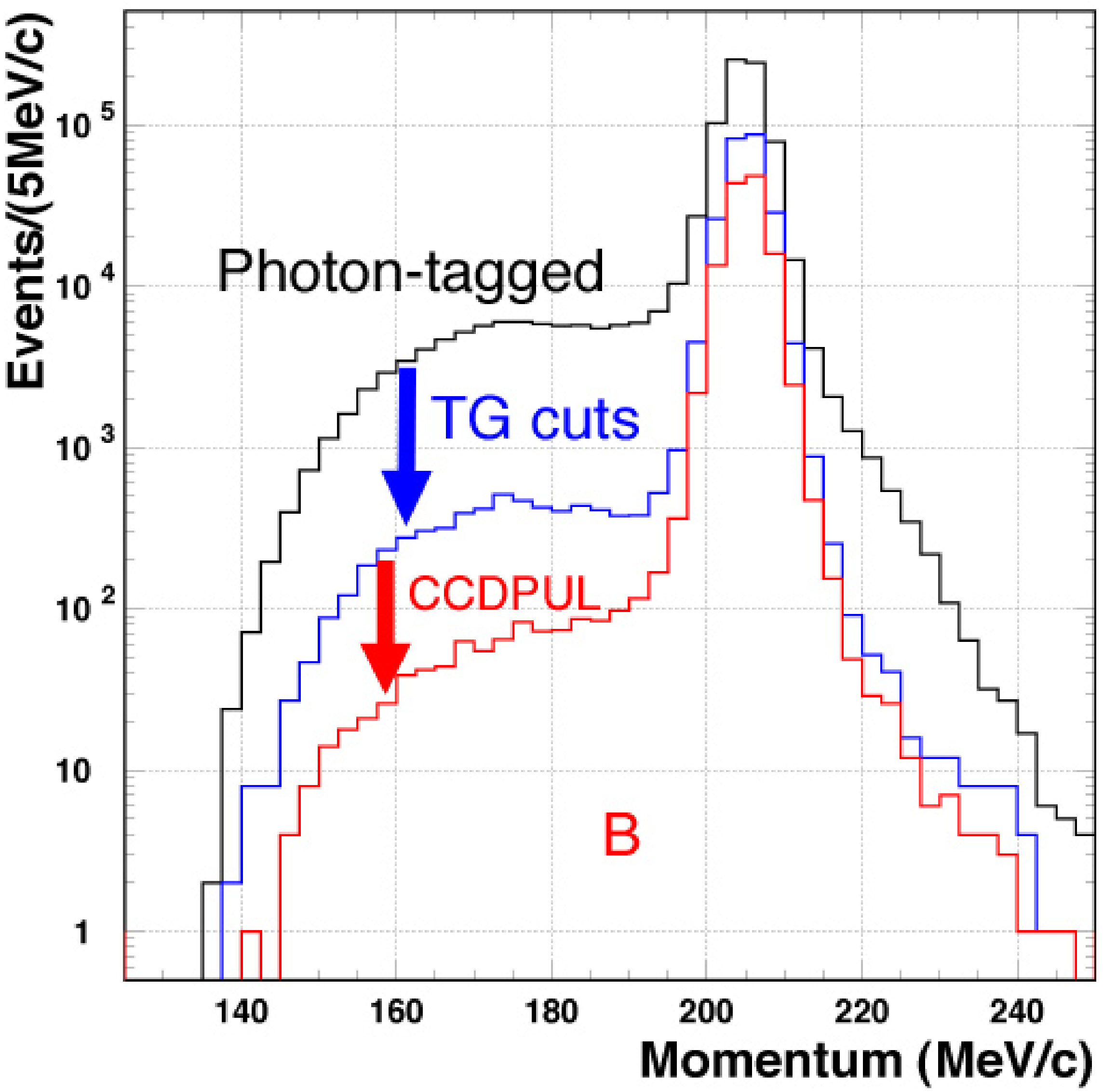
- Identify excess 2^{nd} pulse energy in K^+ fibers.
  - Excess energy $> 1.25 MeV$ is cut.
- Identify events where the total K^+ energy in TG does not match the expected range in TG.



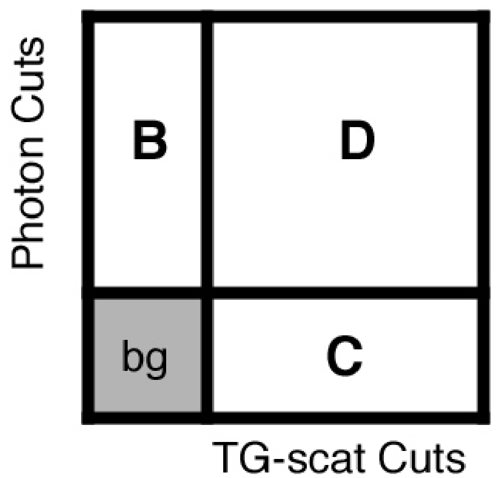


Measuring $K_{\pi 2}$ TG-Scatter Background





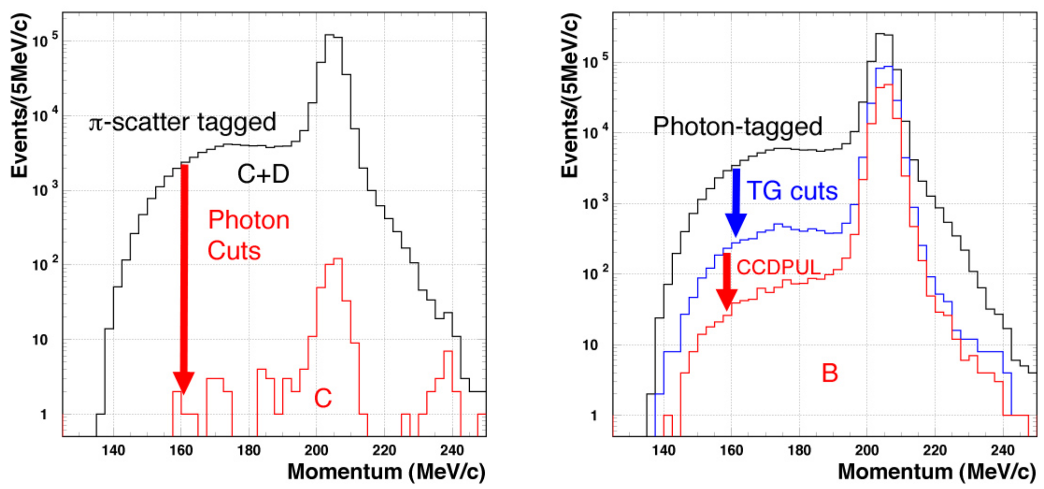
Measure Rejection of Photon Cuts



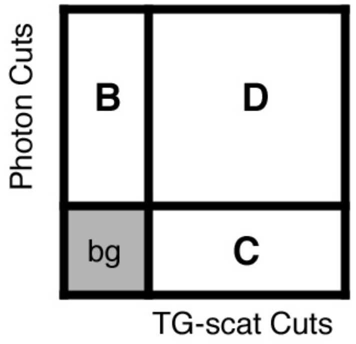
Obtain # of events remaining with Photon-tagged sample (normalization).

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

- Obtain multiple TG-scatter samples using combinations of:
  - Excess 2^{nd} pulse energy
  - K^+ energy/range matching
  - TG π^+ track observed/expected



- Photon-tagged sample ("Normalization") contaminated with
  - $K_{\pi 2}$ scatters in Range Stack
  - $K^+ \to \pi^+ \pi^0 \gamma$



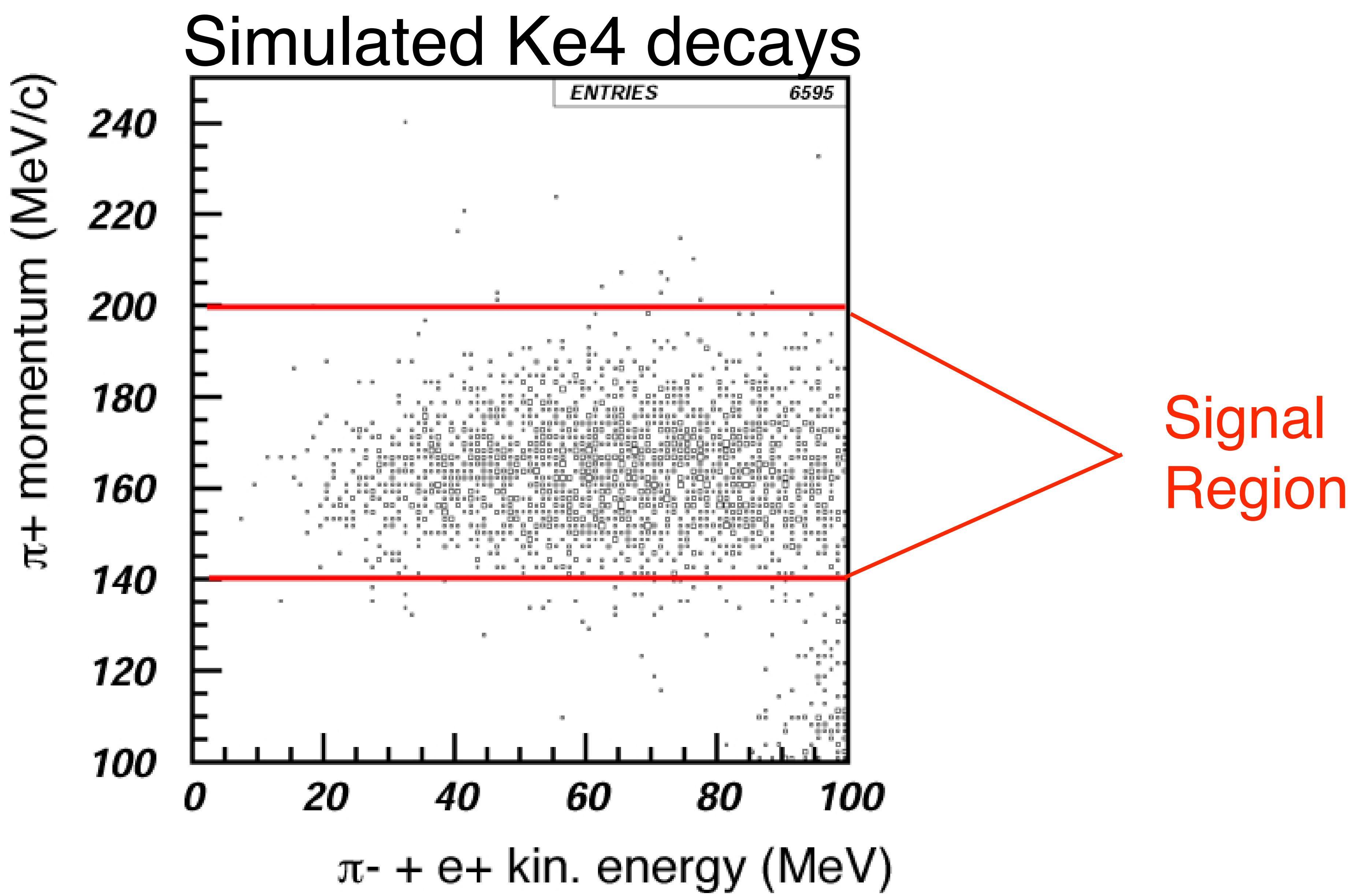
"The enemy of my enemy is my enemy.
Dick Tracy (*Dick Tracy* -1990)

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	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2 \gamma}$	$0.076 \pm 0.007 \pm 0.006$

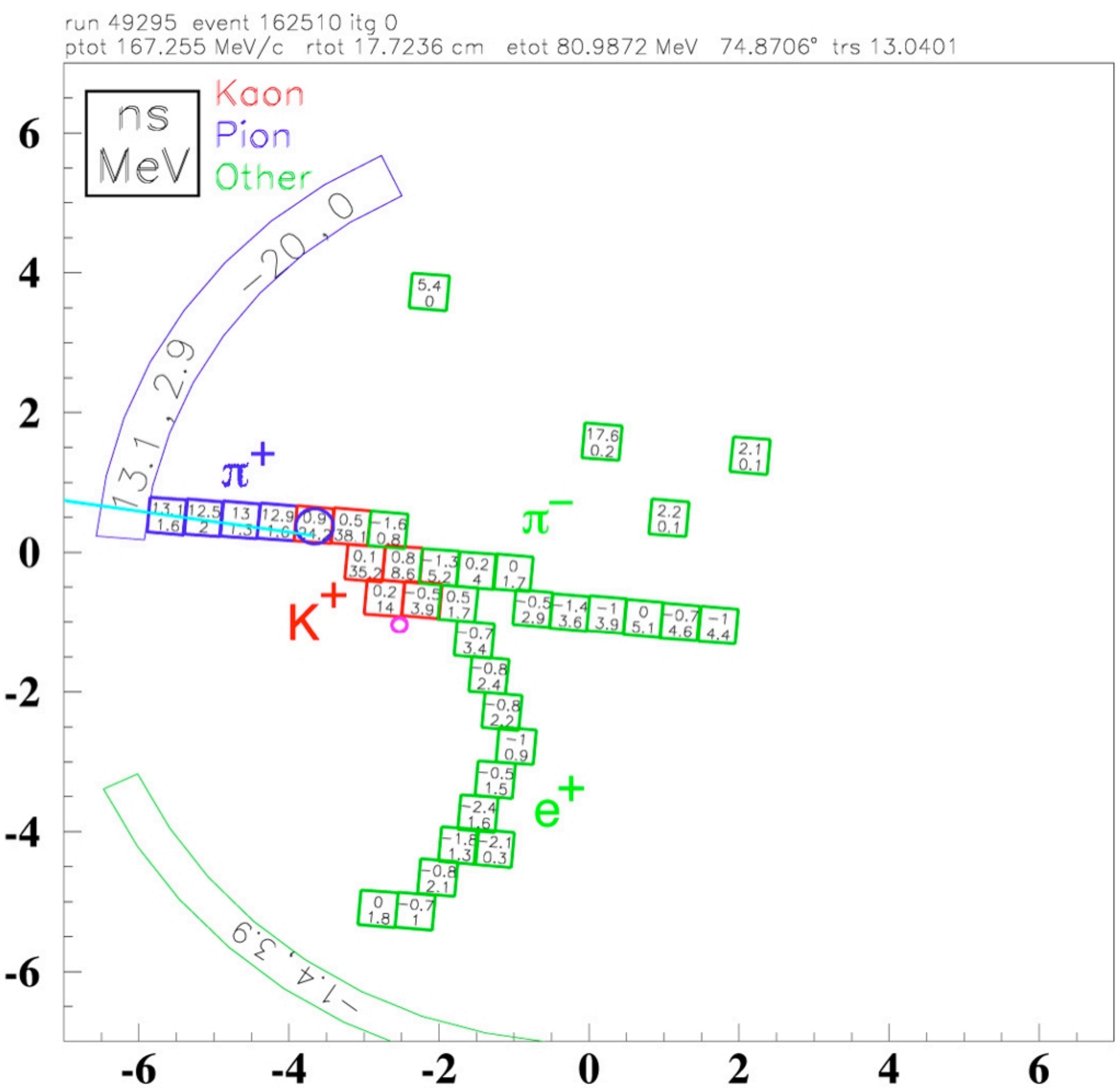
$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4}) Background

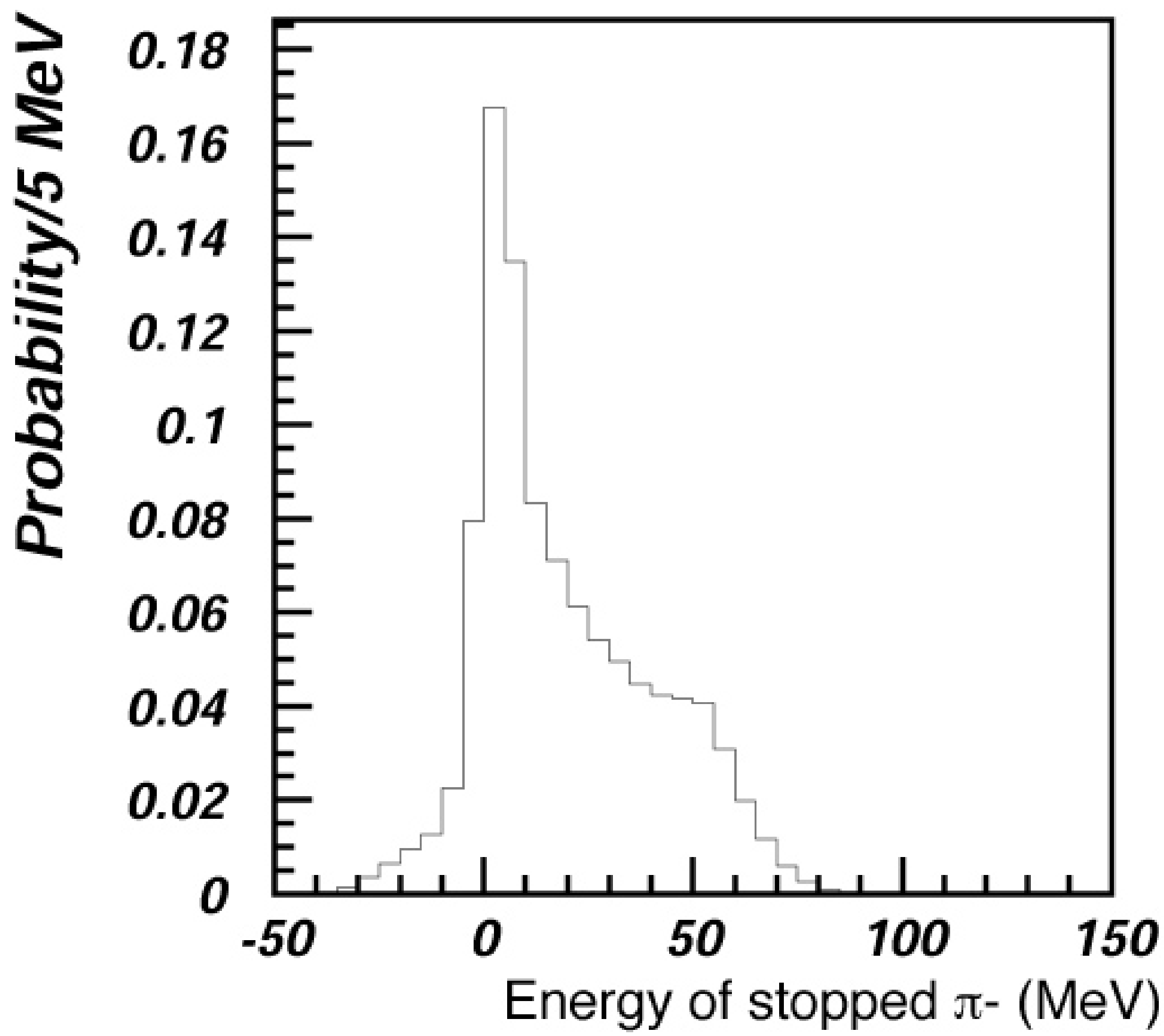
- $\mathrm{K}^+ \to \pi^+\pi^-e^+\nu$ can be a background if the π^- and e^+ go undetected.
  - i.e. have very little kinetic energy.



- Obtain Ke4 sample by target-pattern recognition.

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





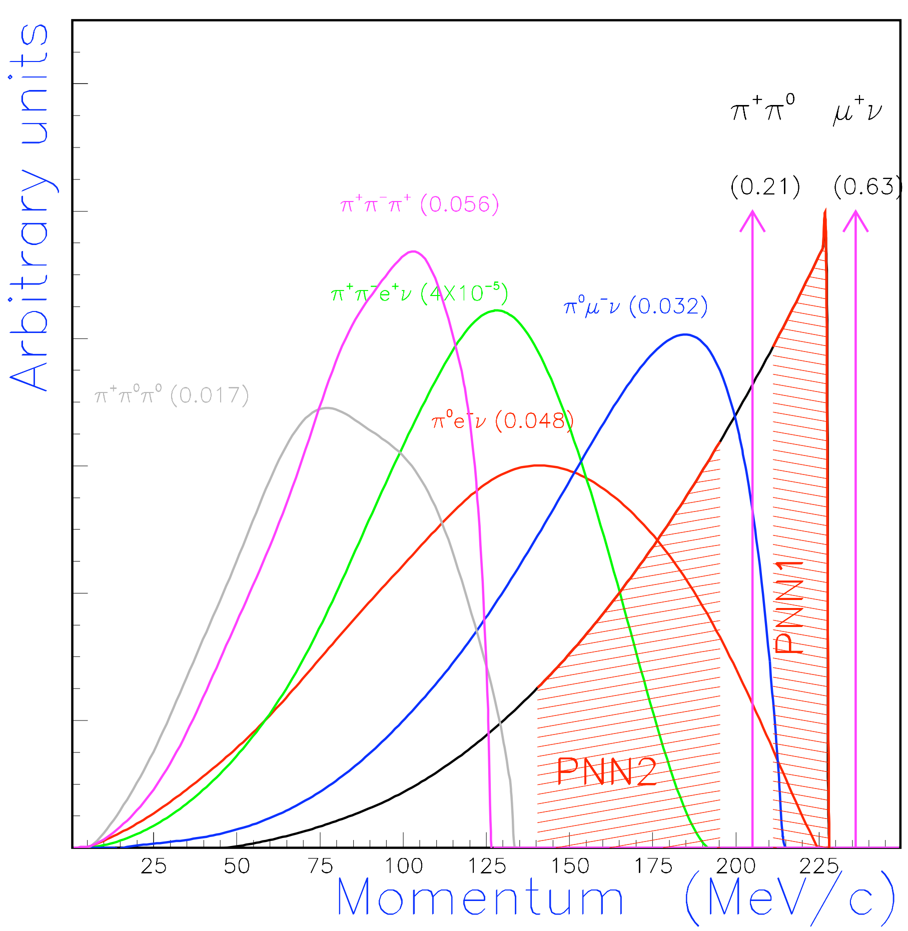
Muon Background

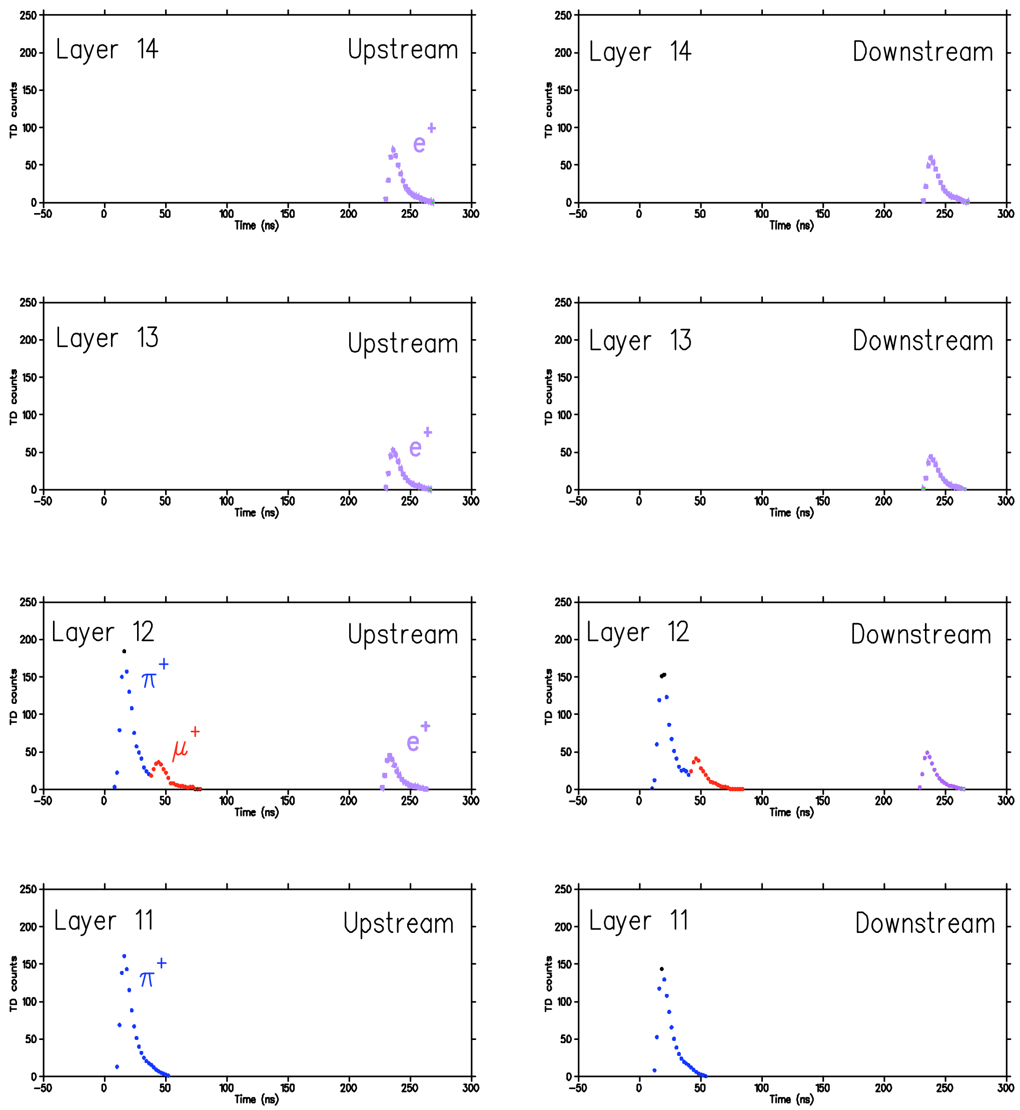
- Initial E949-pnn2 analysis showed that muon background due to $K^+ \to \mu^+\nu$, $K^+ \to \mu^+\nu\gamma$ and $K^+ \to \mu^+\pi^0\nu$ was small (~ 0.001 events).

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

  - Background increased $\times 10$

    still small number.





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

Total Background and Sensitivity

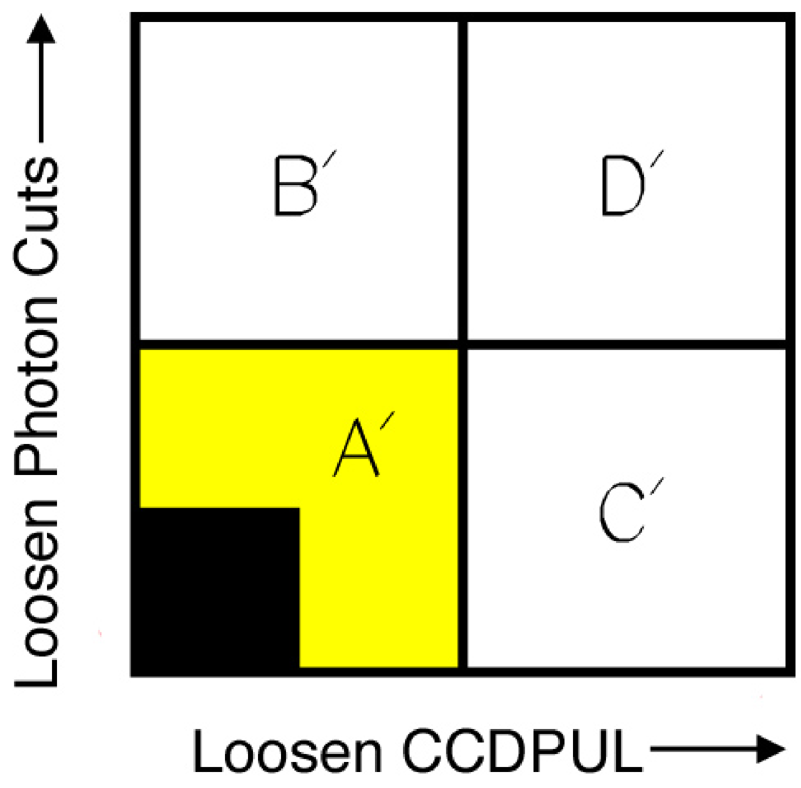
Bkgd Process	Bkgd Events E949	Bkgd Events E787
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ±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



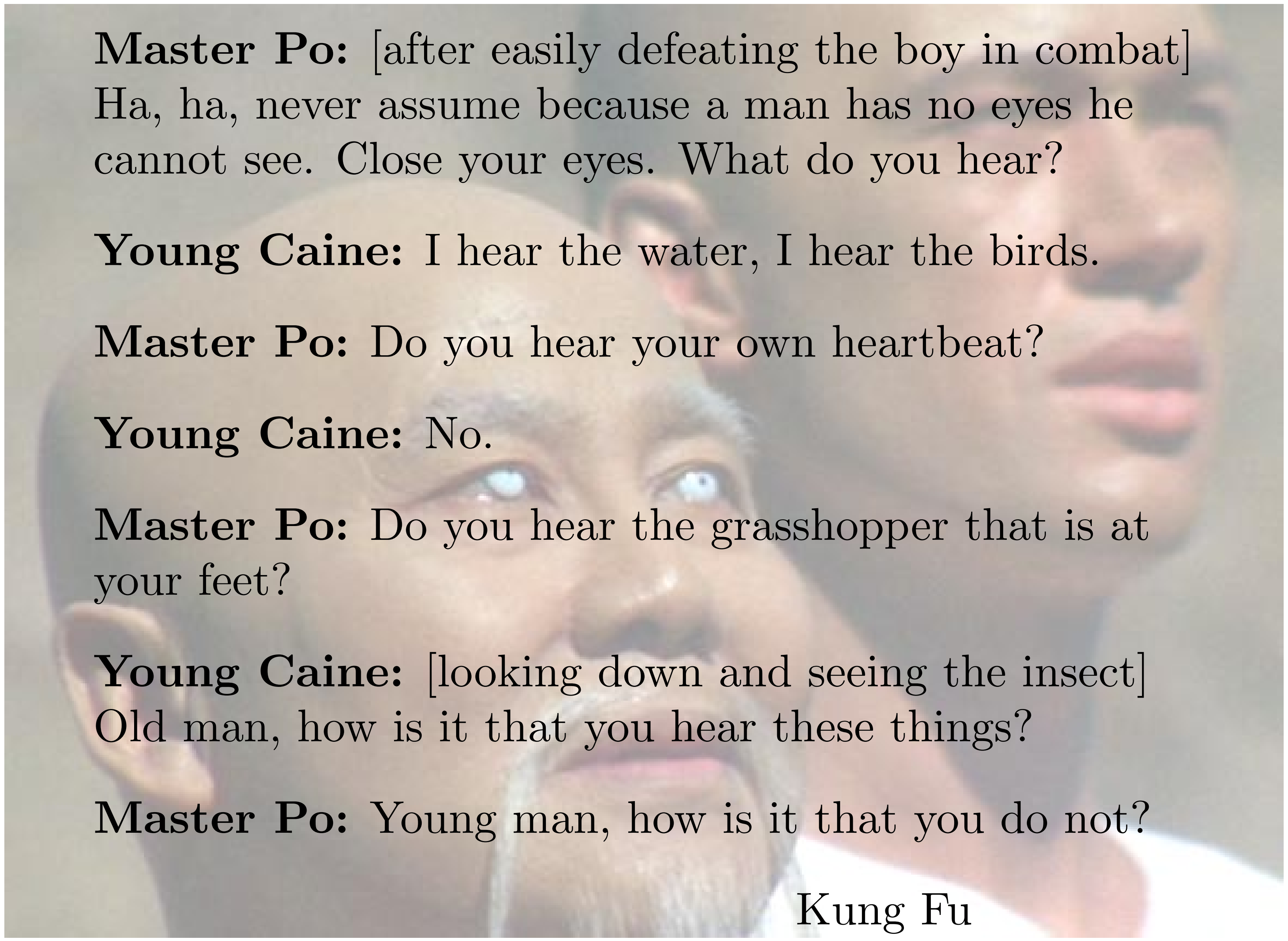
Region	N_{exp}	N_{obs}
CCD_L	$0.79^{+0.46}_{-0.51}$	0
PV_L	$9.09^{+1.53}_{-1.32}$	3
PV_{looser}	$32.4^{+12.3}_{-8.1}$	34

- 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_{exp} is taken into account.

Tightened Regions

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

Signal Region



Master Po: [after easily defeating the boy in combat] Ha, ha, never assume because a man has no eyes he cannot see. Close your eyes. What do you hear?

Young Caine: I hear the water, I hear the birds.

Master Po: Do you hear your own heartbeat?

Young Caine: No.

Master Po: Do you hear the grasshopper that is at your feet?

Young Caine: [looking down and seeing the insect] Old man, how is it that you hear these things?

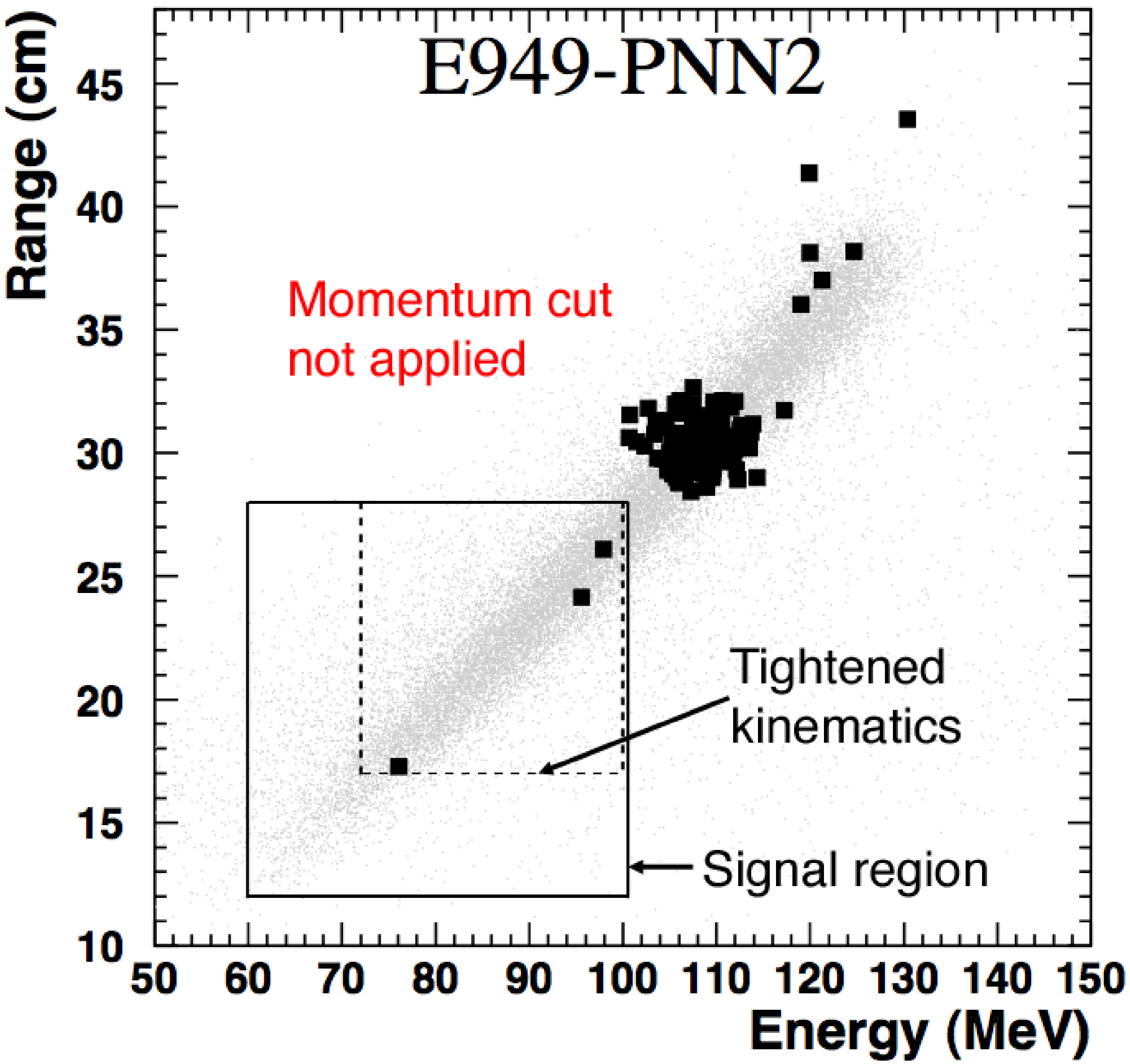
Master Po: Young man, how is it that you do not?

Kung Fu

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

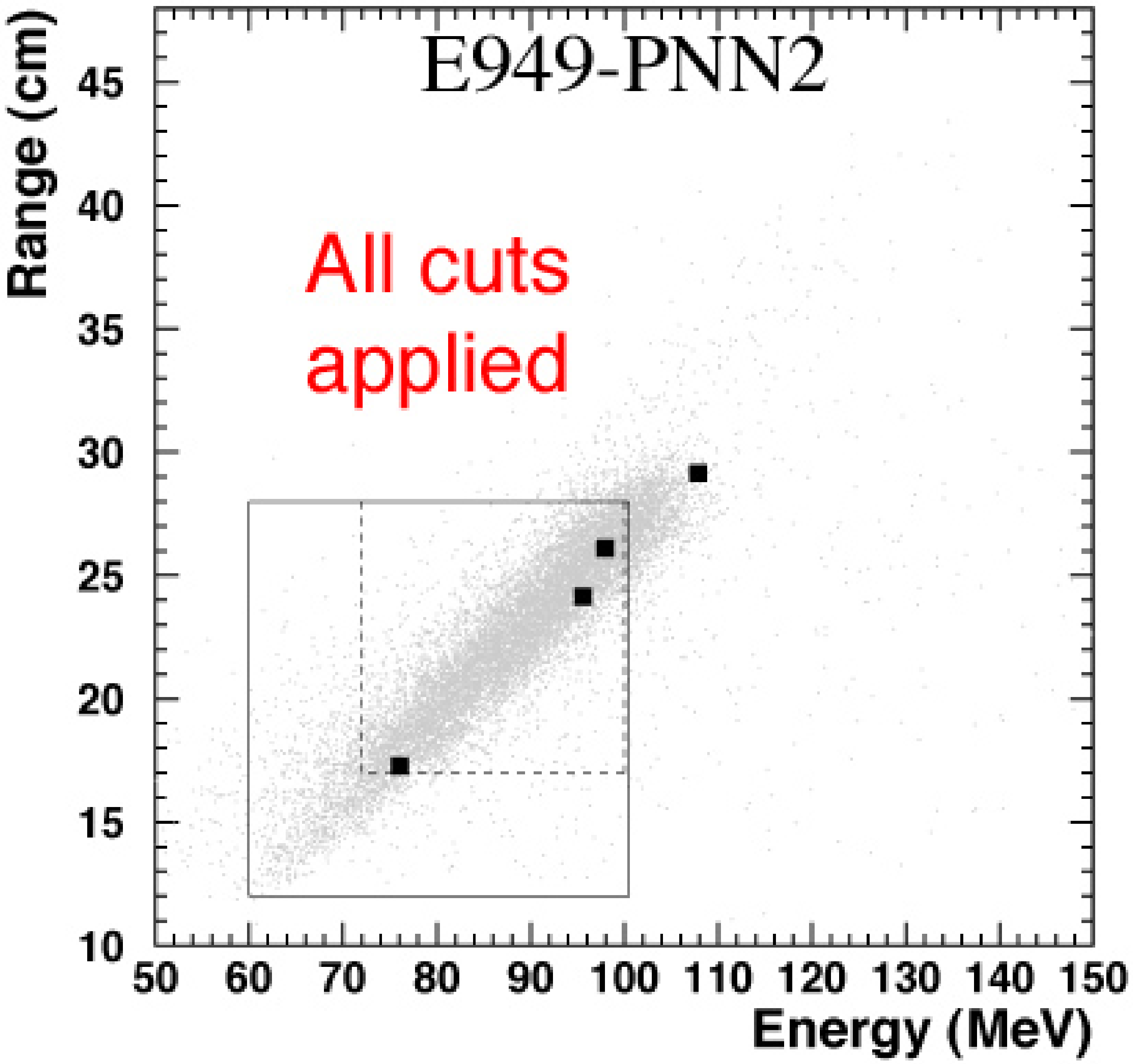
Signal Region



The nine cells

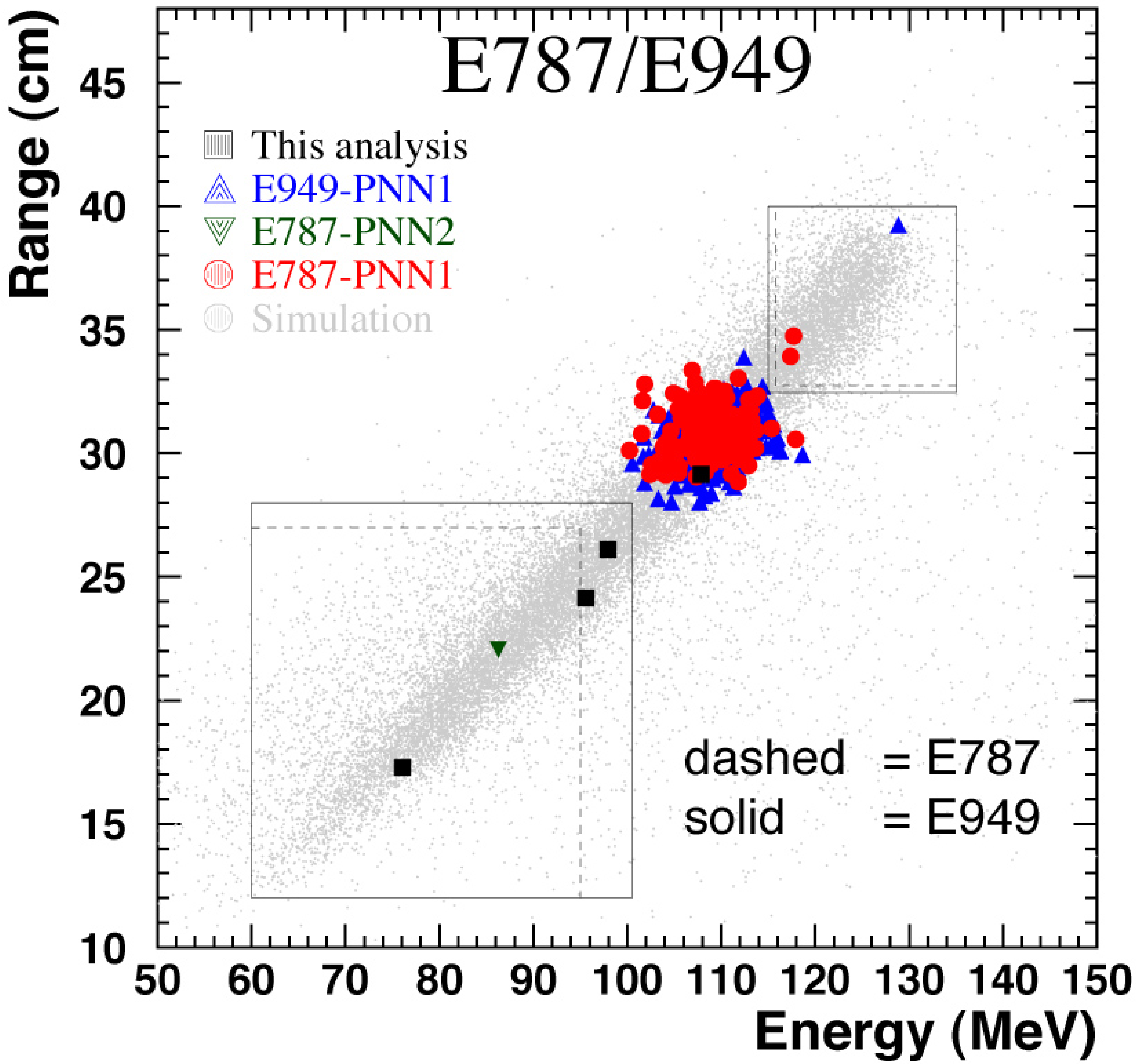
Bkgd	Events	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20

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: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$

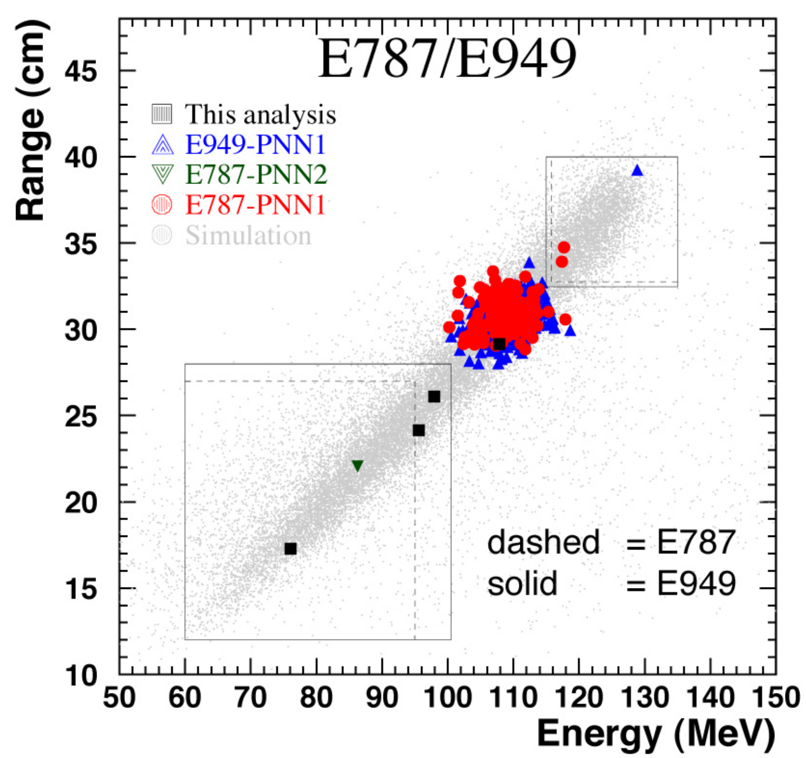
All E787 & E949 Data



- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
- 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 from E787+E949

- In 25 years and 3 detector upgrades, E787 & E949:
  - observed 7 $K^+ \to \pi^+ \nu\bar{\nu}$ (candidate) events, rest of world - zero.
  - obtained a branching ratio of $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$, previously a limit of $< 1.4 \times 10^{-7}$ (90%CL) existed.
- DOE only gave 20% of promised running time:
  - $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ twice as large, but still consistent with, the Standard Model expectation of $(0.85 \pm 0.07) \times 10^{-10}$.
  - Standard Model only in "tension"
- 100% of promised running time... priceless.



extras

$K^+ \to \pi^+\pi^-e^+\nu$ (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.