New measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio

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Brookhaven National Laboratory

2008 at Cornell, U. Wisconsin and Fermi Lab

E787 and E949 collaborators

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

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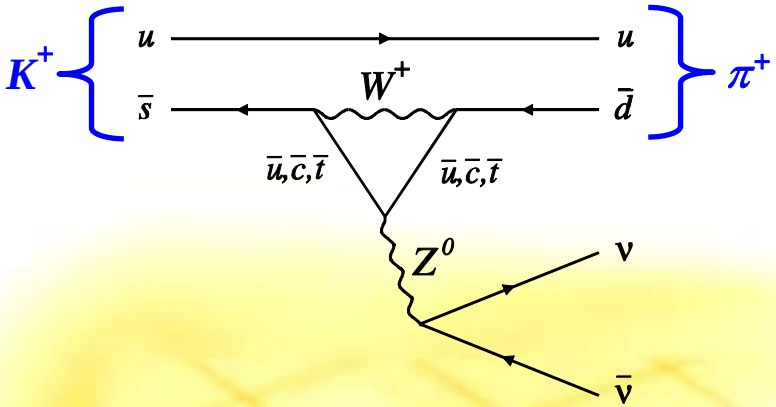
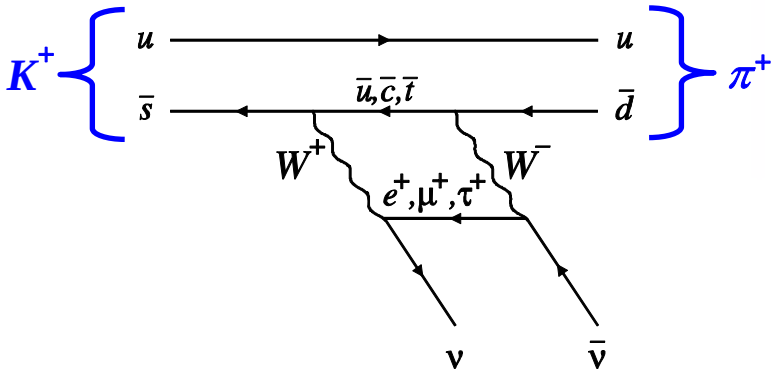
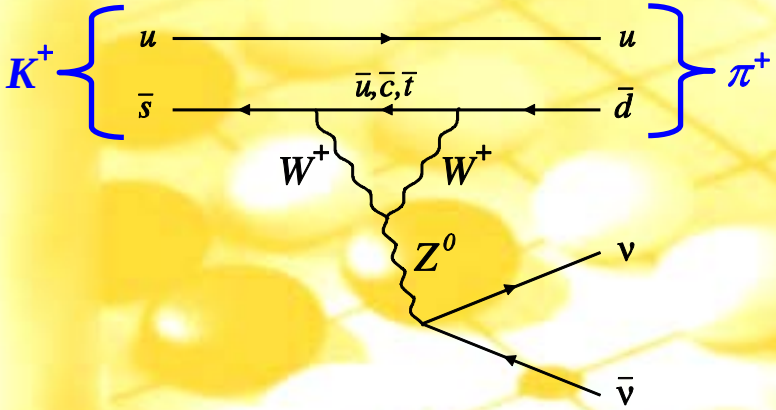
$K^+ \to \pi^+ \nu\bar{\nu}$ in standard model (SM)

	Quark contents	Mass (MeV/c^2)	Lifetime (ns)
K^+	$u\bar{s}$	493.7	12.4
π^+	$u\bar{d}$	139.6	26.0
ν	-	≈ 0	∞



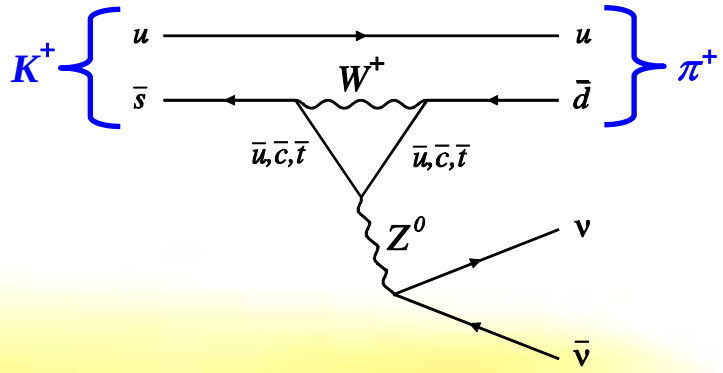




FCNC is permitted through loop diagrams, however it is highly suppressed.

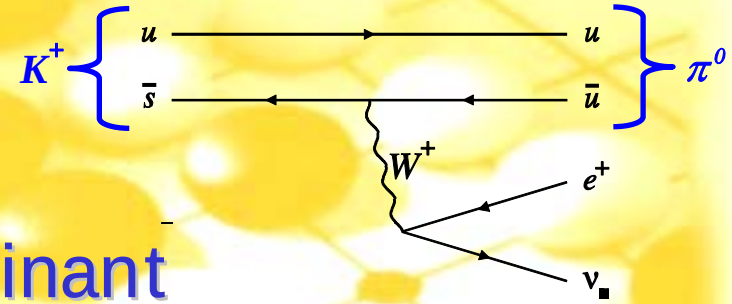
Branching ratio prediction

Effective Hamiltonian:



$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W}$$

$$\cdot \sum_{l=e,\mu,\tau} [V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_t)](\bar{s}d)_{V-A}(\bar{\nu}_l \nu_l)_{V-A}$$



X: Wilson coefficients

Short-distance interaction dominant

Relevant hadronic operator matrix element can be extracted from $K^+ \to \pi^0 e^+ \nu$

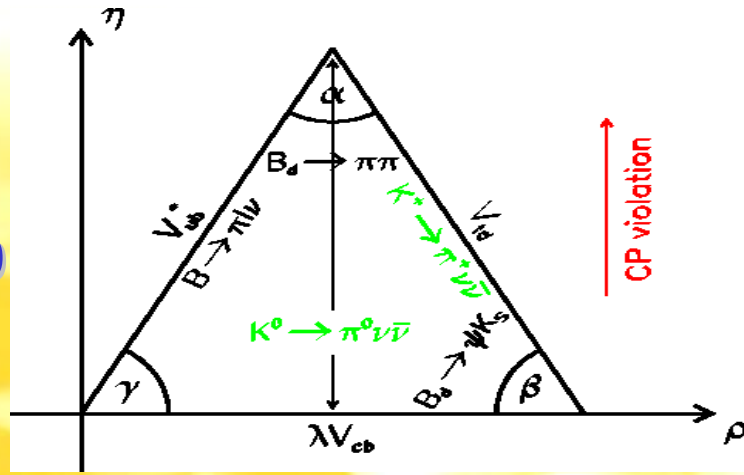
M.K. Gailard and Benjamin W. Lee 1974

Rare process BR~10^{-10} with small theory uncertainty (8%)

Precise theory prediction: $(0.85 \pm 0.07) \times 10^{-10}$

(50% of the error is from CKM parameters)

arXiv: hep-ph/0405132 Andrzej J. Buras, et. al.



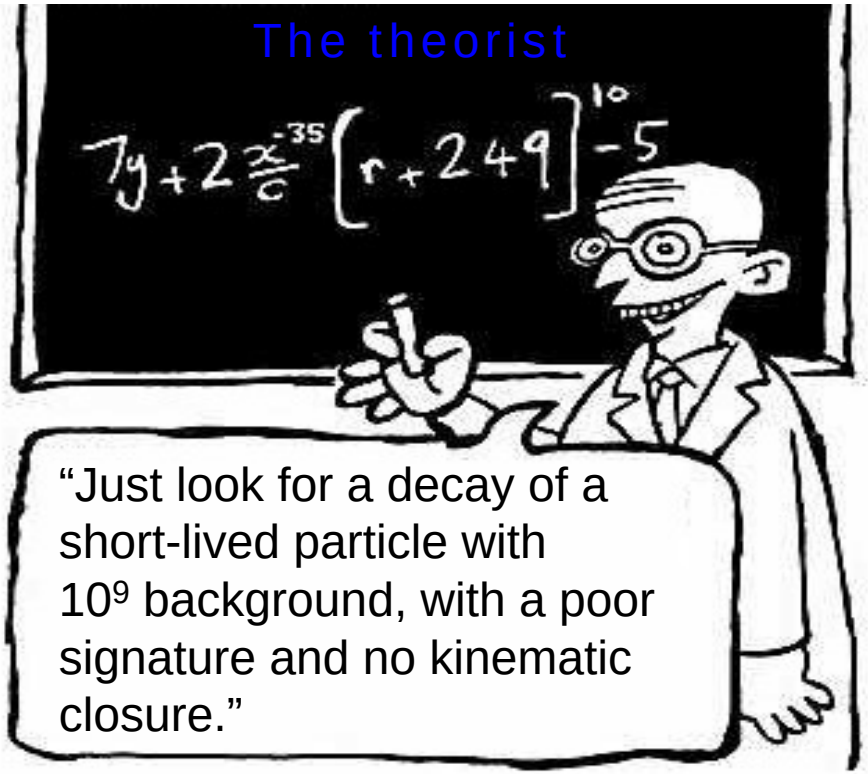
top quark contribution ~70%

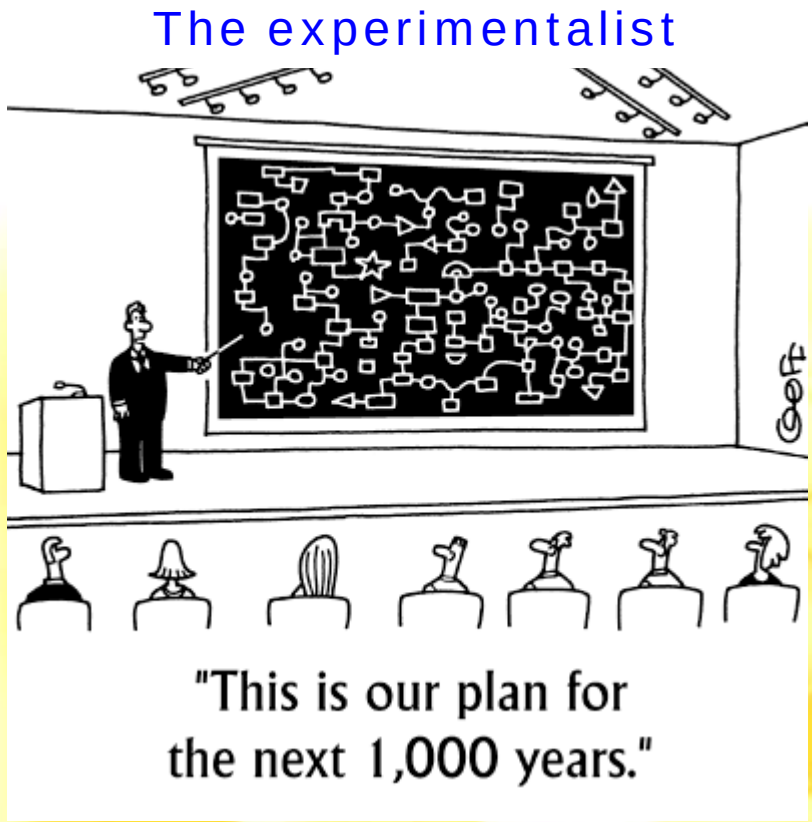
(sensitive to V_{td})

Probe SM at quantum level, thereby allowing an indirect test of high-energy scales through a low-energy process

(sensitive to new physics)

Searching for the holy grail





Marco S. Sozzi at CKM2008

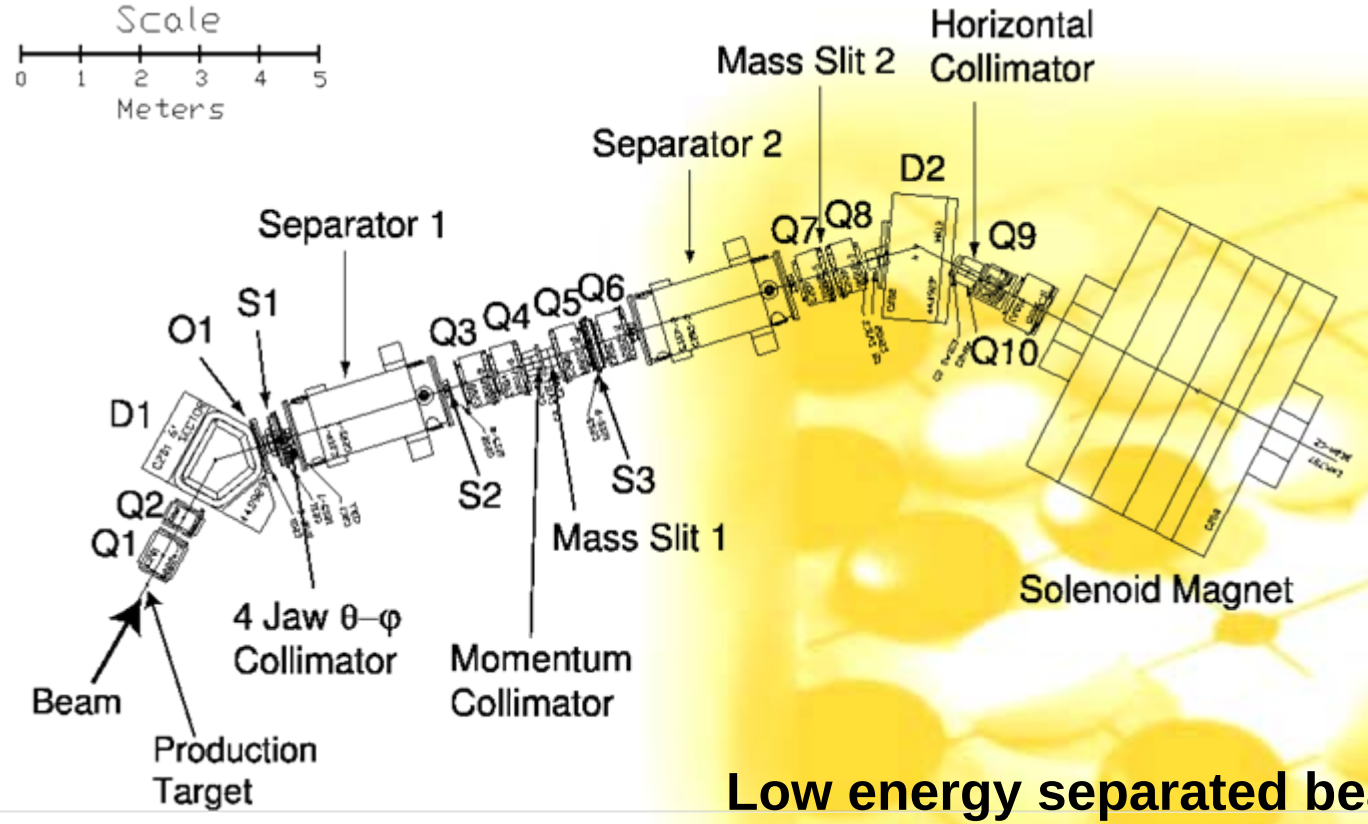
High intensity K^+ beam is supplied by AGS

Alternating gradient synchrotron

6×10^{12} protons/2 sec-long spill/ 5 sec **3.5×10^{6} incident K^+/spill**

21 GeV/c

Proton beam ⟶ Pt target ⟶ K^+ beam ⟶ Detector



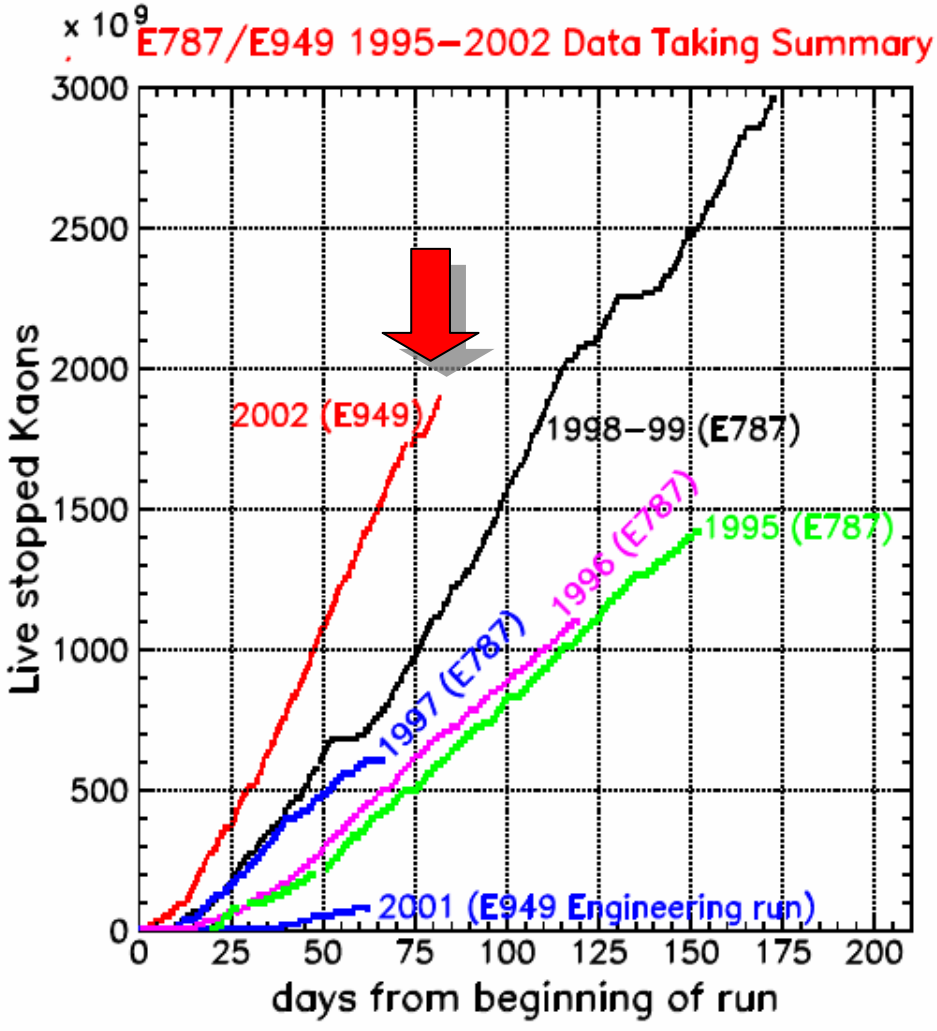
Low energy separated beamline

$K^+ : \pi^+ \sim 3 : 1$

Data taking 1.7×10^{12} stopped K^+ (this study)

- $\pi^+\nu\bar{\nu}$ trigger

  142×10^6 on tape
- $K^+ \to \pi^+\pi^0$ monitor
- $K^+ \to \mu^+\nu$ monitor
- beam π^+ scattering
- Charge exchange ($K^+n \to K^0p$, $K^0_S \to \pi^+\pi^-$)

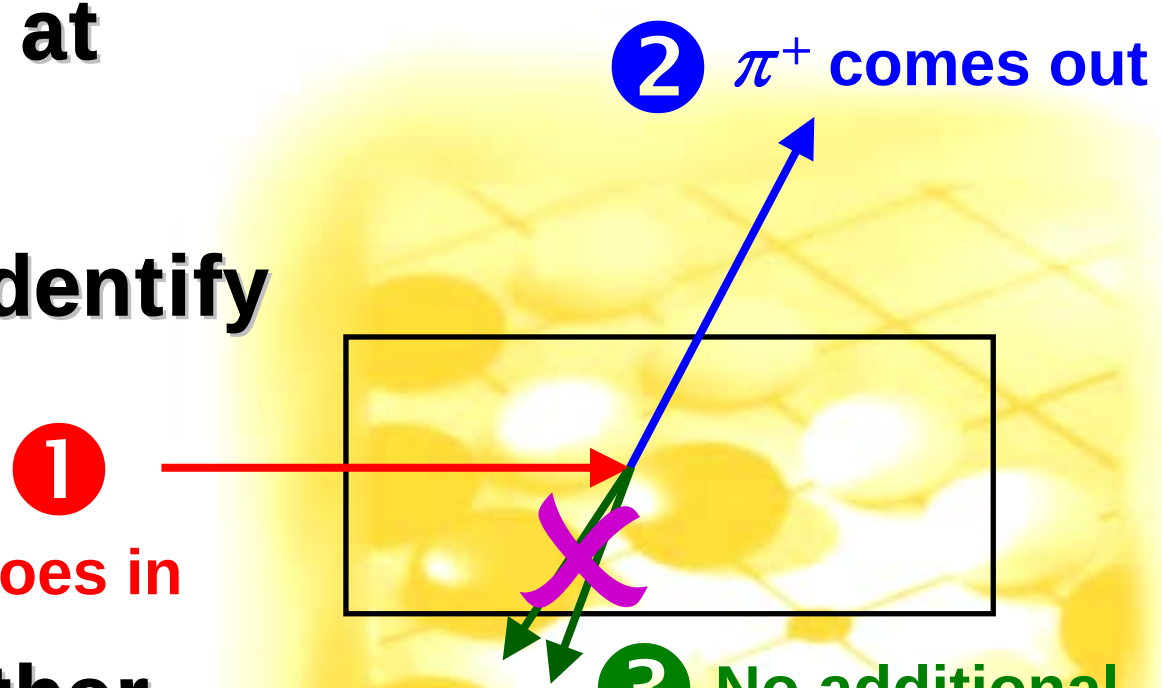


Big picture for searching $K^+ \to \pi^+ \nu\bar{\nu}$

1. K^+ stop in detector target and decay at rest

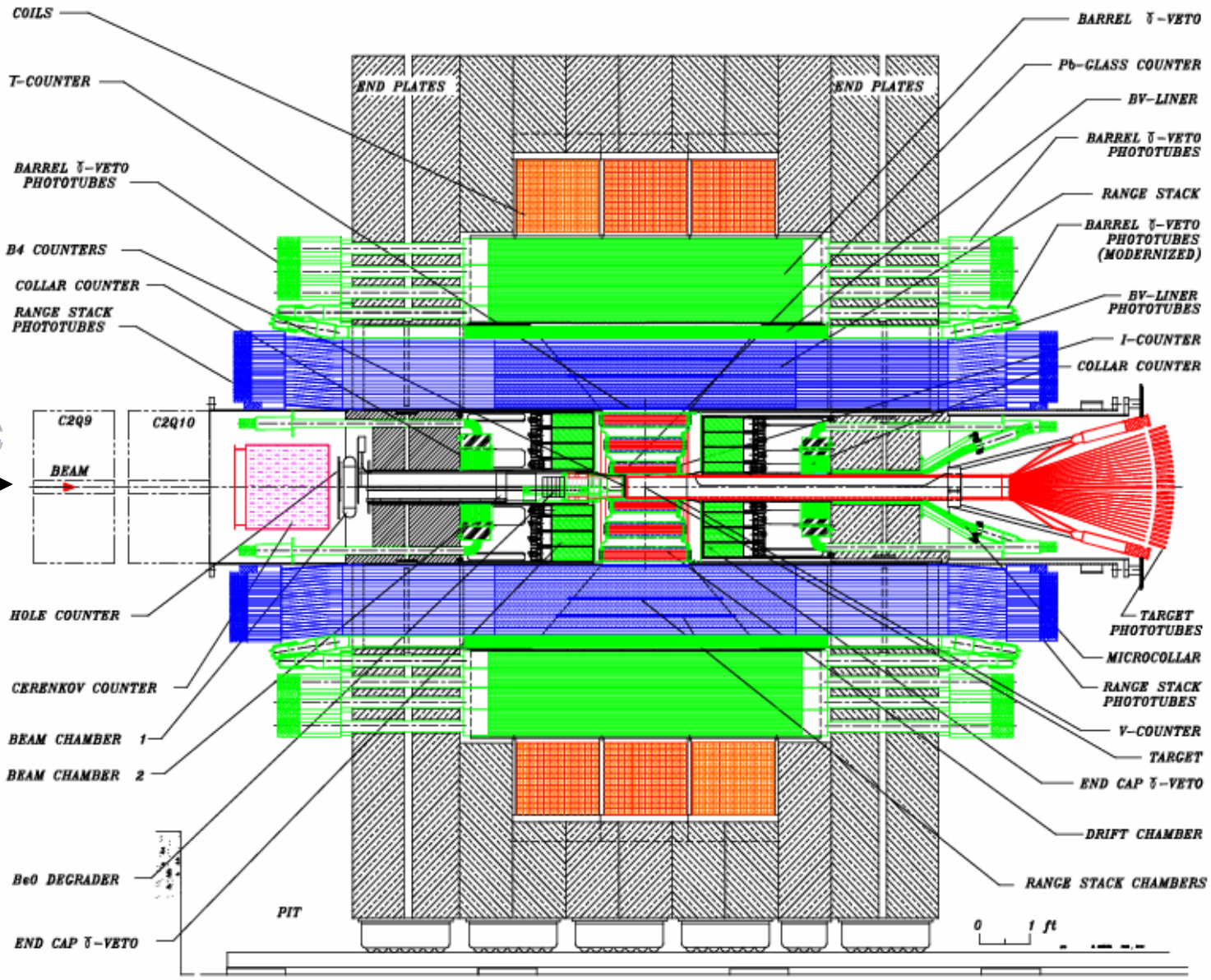
2. Measure and identify π^+

3. Veto on any other activity in the detector



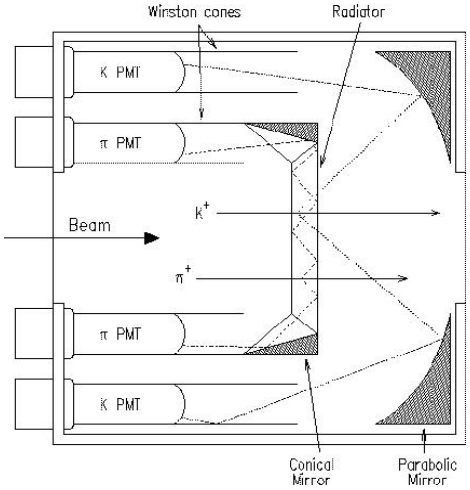
K^+ beam

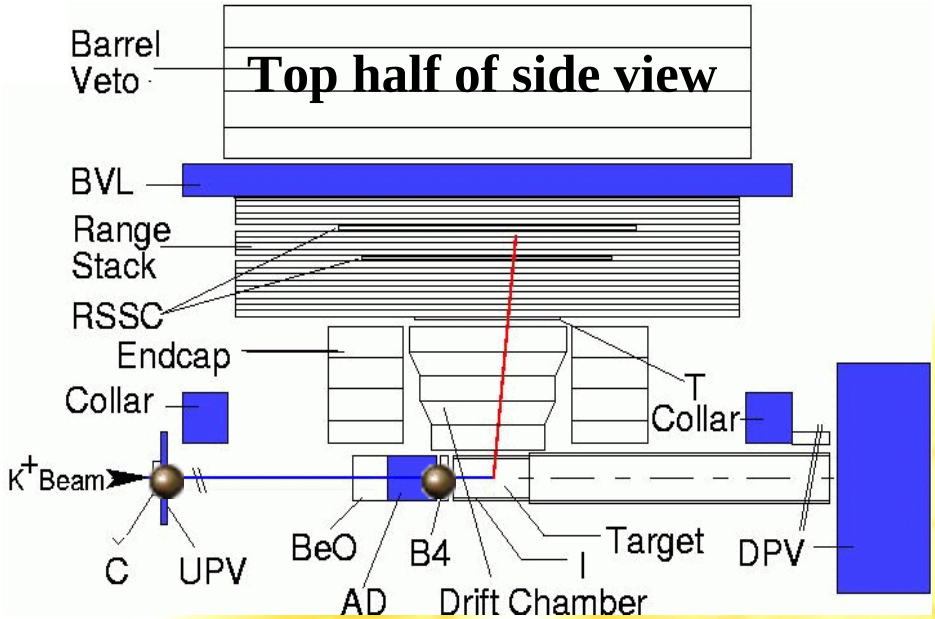
710 MeV/c



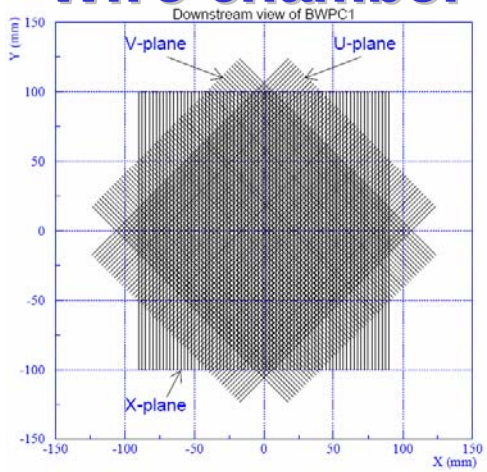
Beam detectors

➢ Cerenkov counter

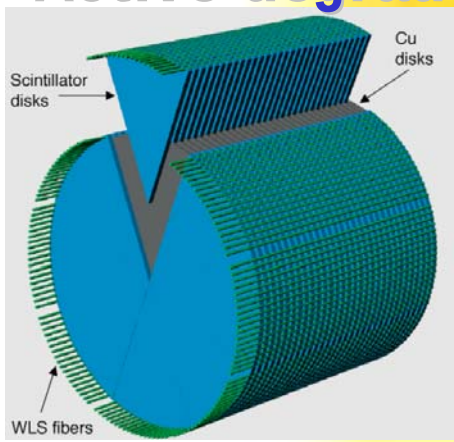




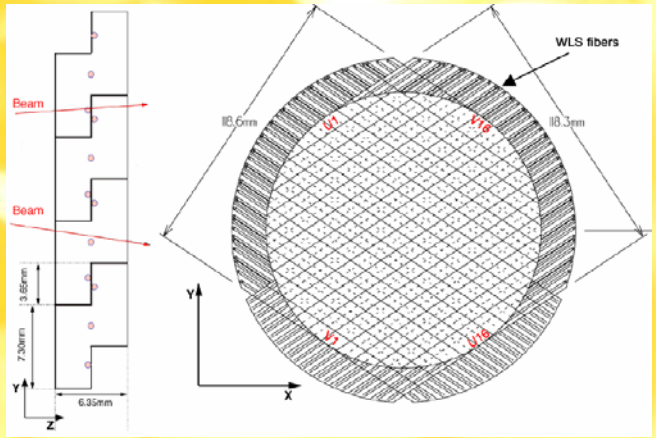
➢ Wire chamber



➢ Active degrader



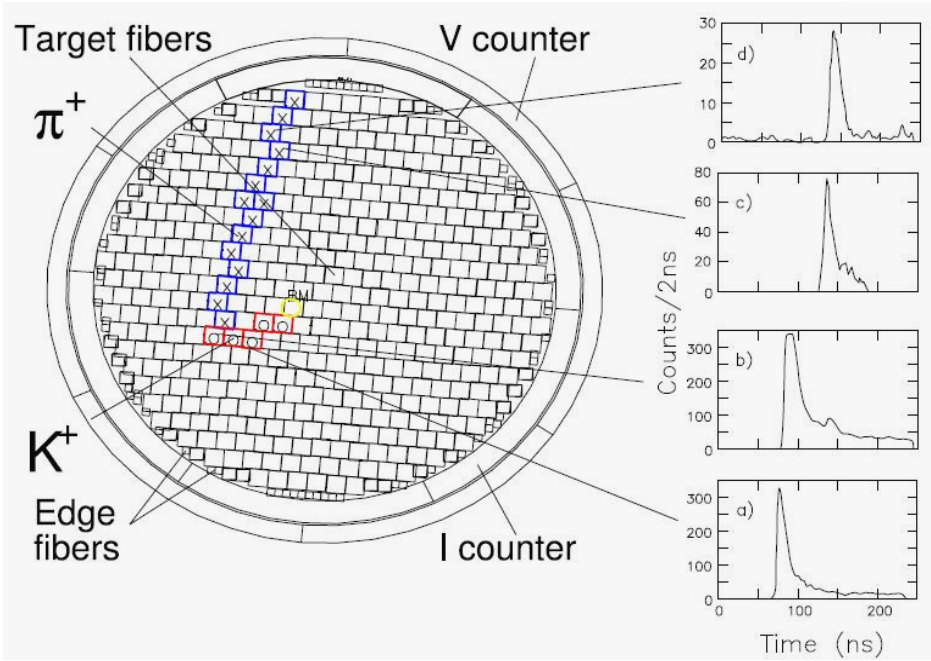
➢ B4 counter

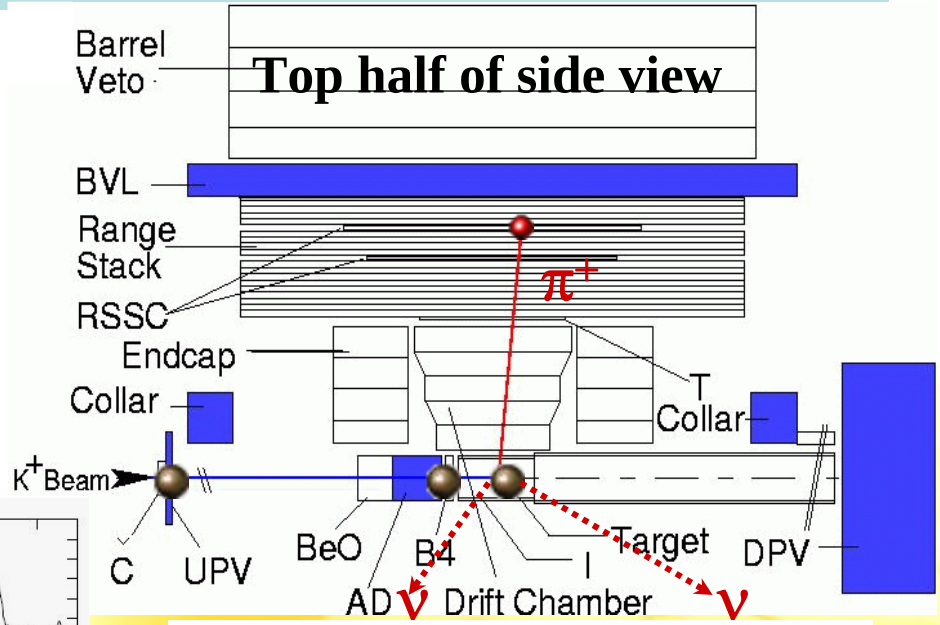


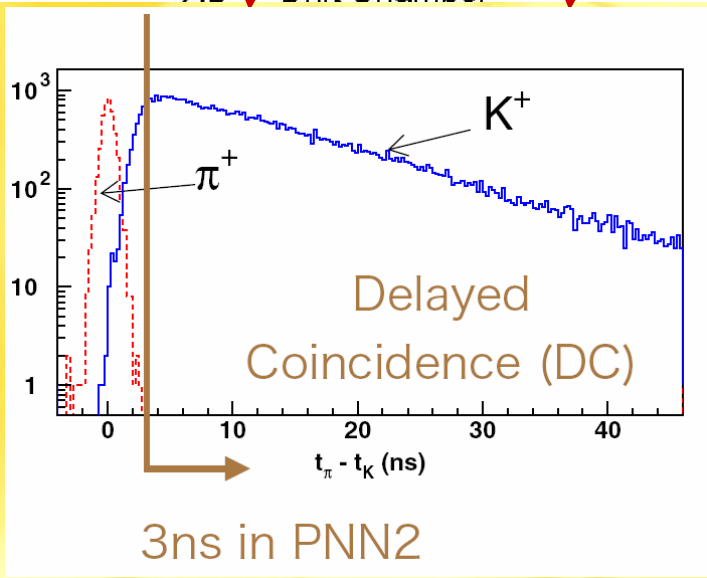
E949 Target

- **Target**
  (ADC, TDC and CCD)
- **I counter**
- **V counter**

End view of target



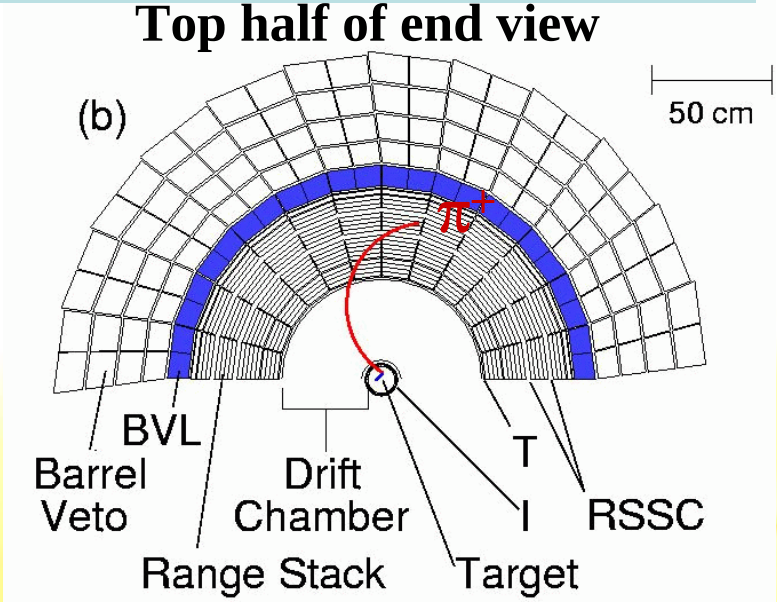


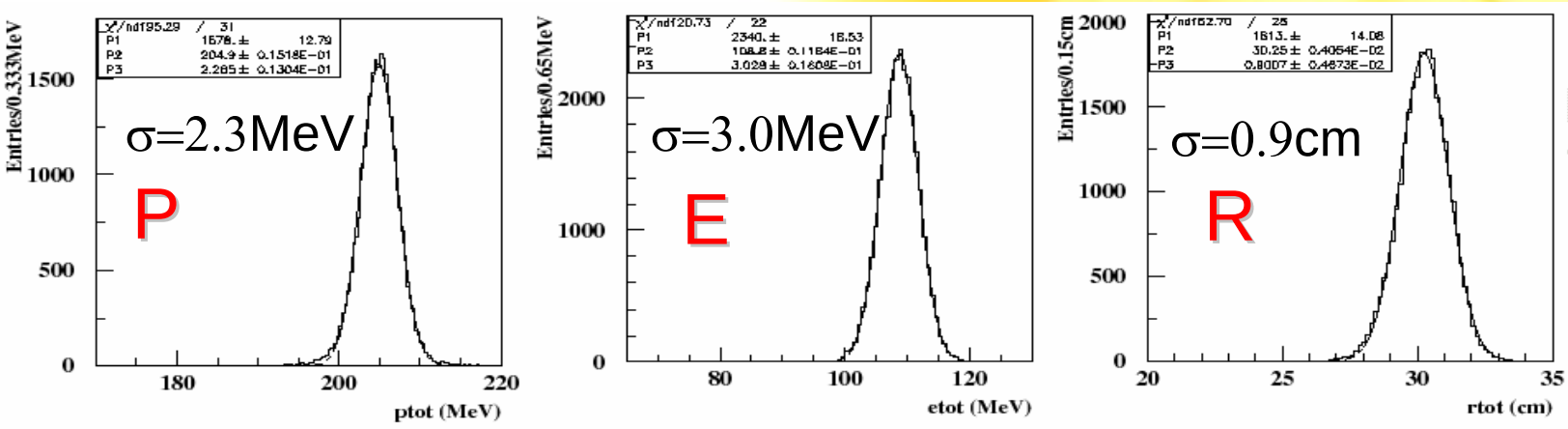


Drift chamber, range stack

- Drift chamber
- Range stack

  Momentum, energy and range measurement





momentum, energy and range of π^+ of $K^+ \rightarrow \pi^+\pi^o$

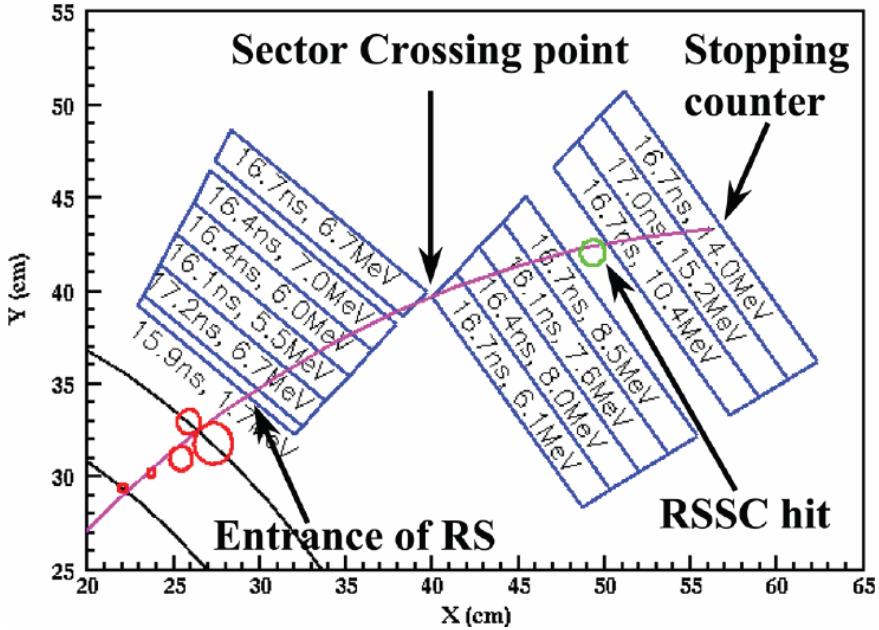
Range stack

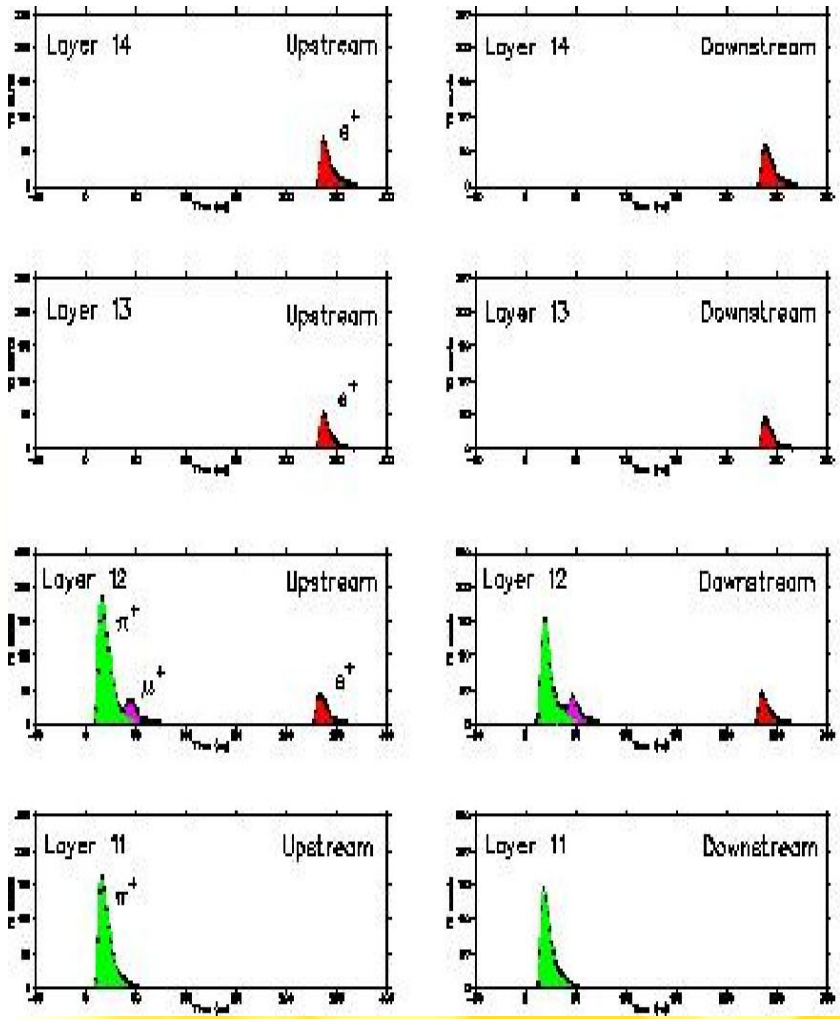
- **Range stack**

  500 MHz waveform digitizer

  Pion, Muon ID
- **Range stack straw chamber**

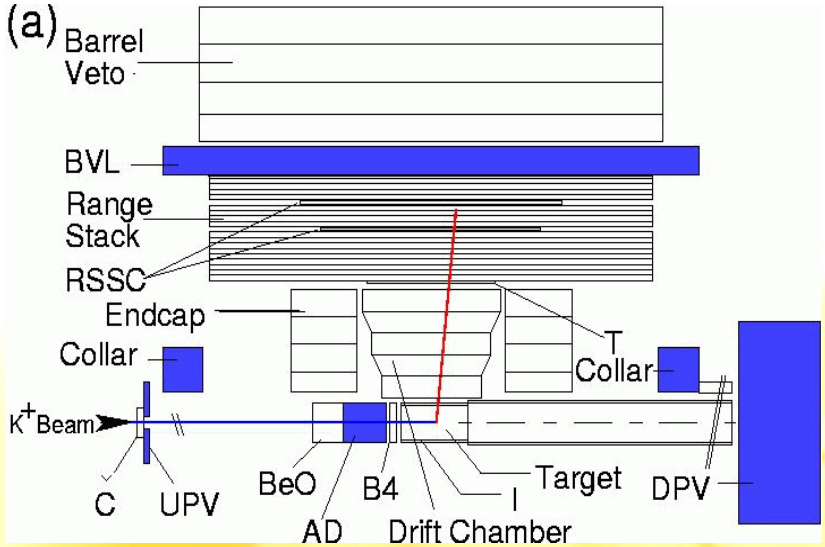
$\pi \rightarrow \mu \rightarrow e$ chain

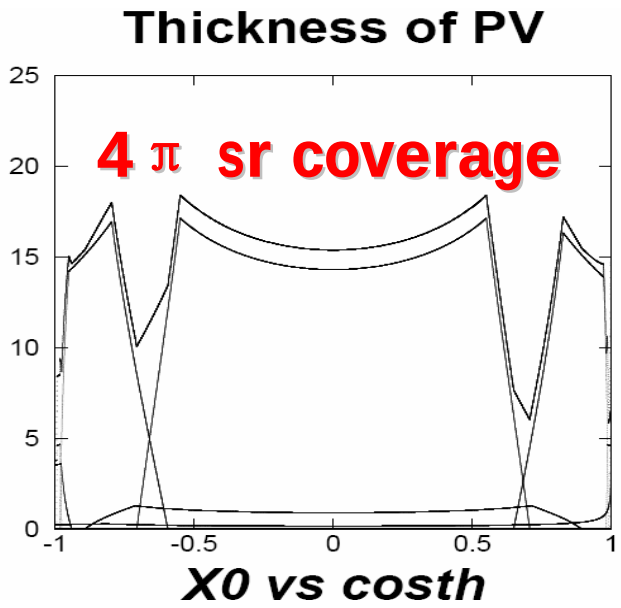


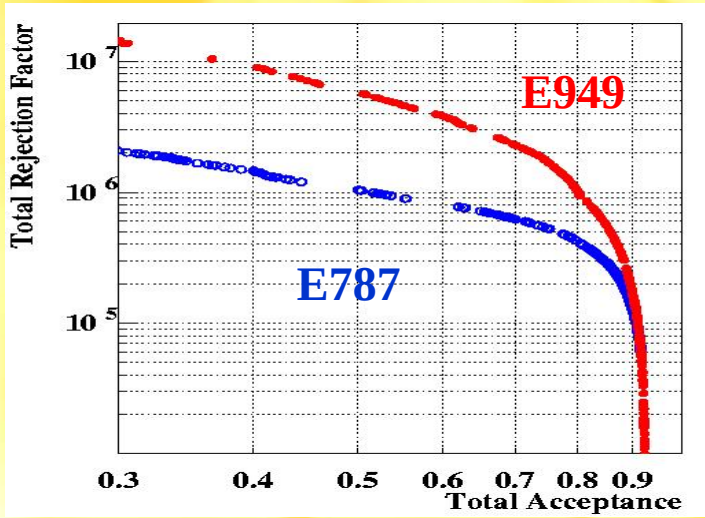


Photon veto detector

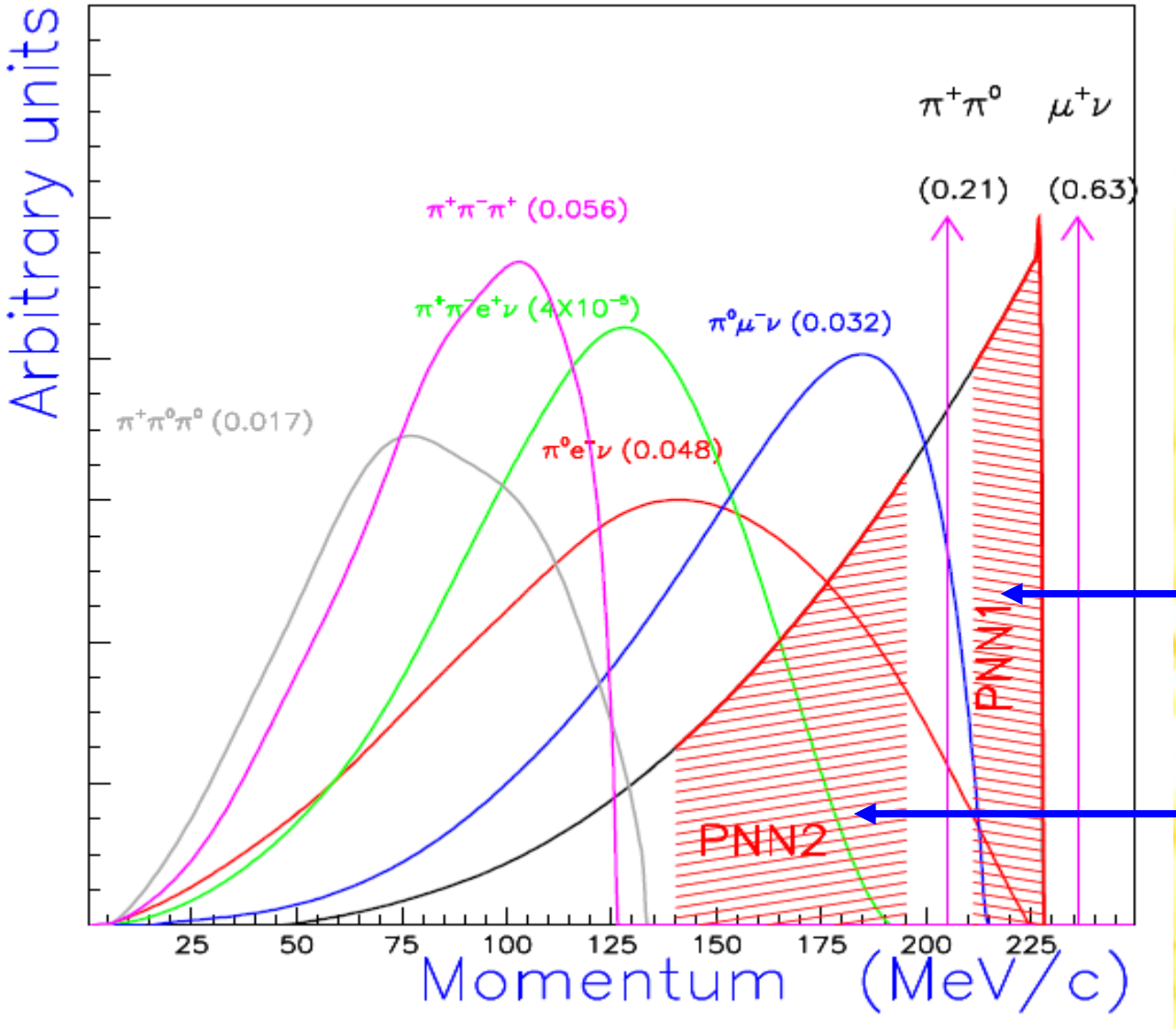
- Active Degrader
- Target fibers
- Endcap veto
- Barrel veto
- Barrel veto liner .....







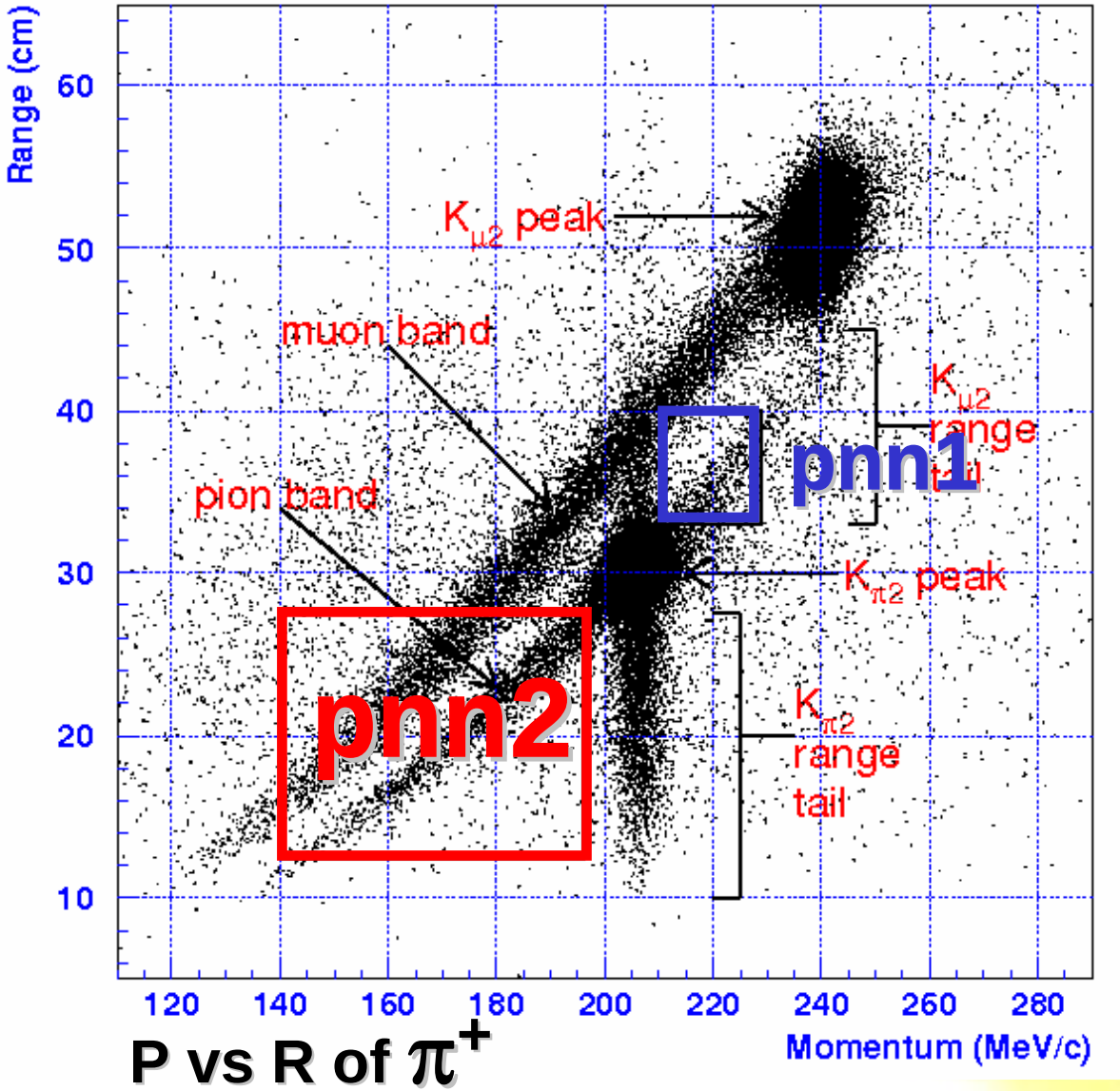
Signal box and background overview



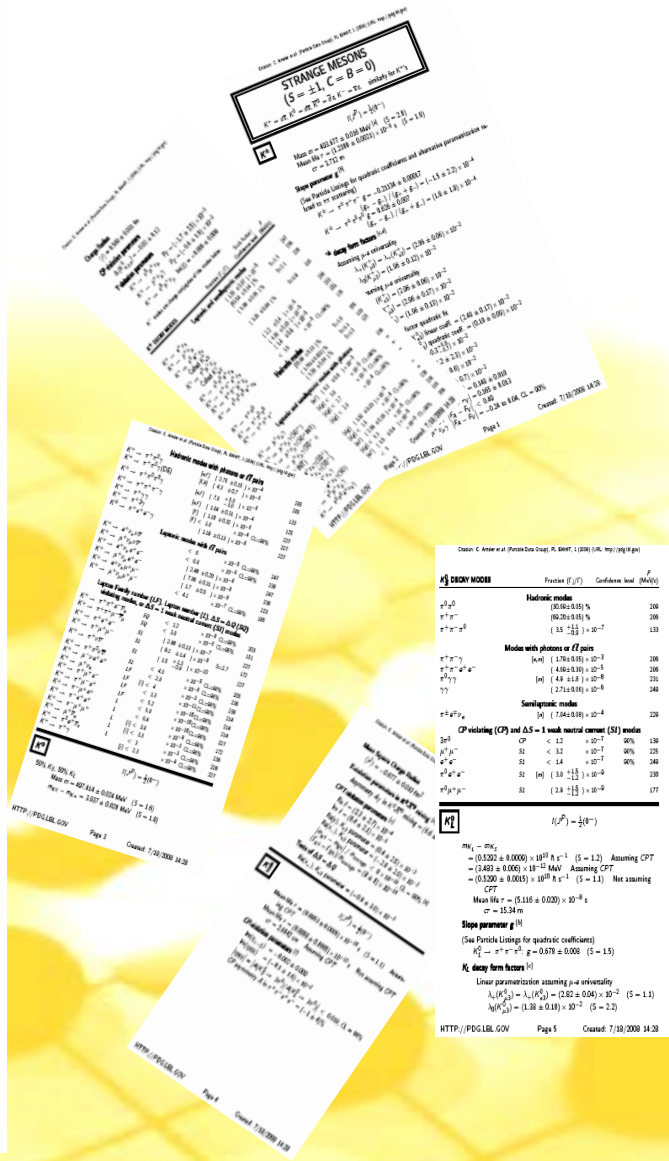
pnn1

pnn2

After the trigger



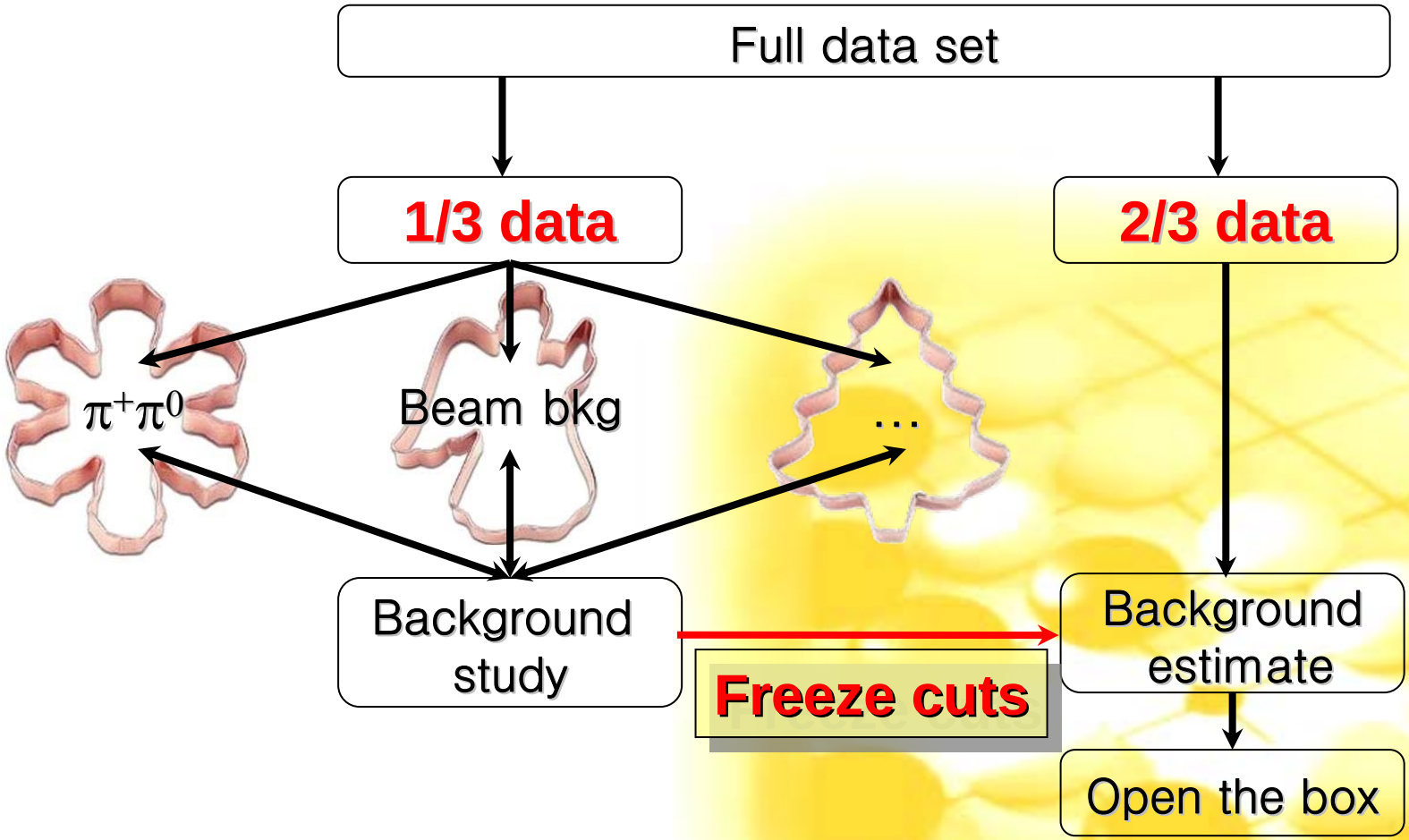
P vs R of π^+



Important background list

Cut / Bkg	Kinematics cuts (P/R/E)	Particle ID (K/π/μ)	Photon veto	Target pattern	Timing cuts
$K^+ \to \pi^+\pi^0$ scattering			√	√	
$K^+ \to \pi^+\pi^0\gamma$	√		√		
Beam		√		√	√
muon	√	√	√		
$K^+ \to \pi^+\pi^-e^+\nu$			√	√	
Charge exchange $K^+n \to K^0p$			√	√	√

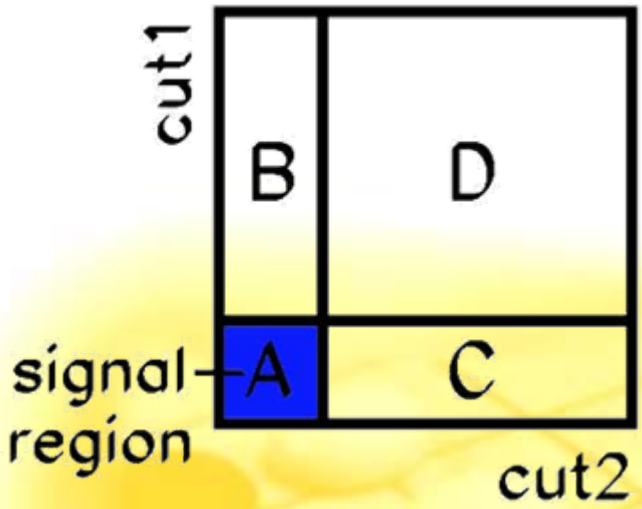
Strategy 1: avoid bias in cut tuning



Strategy 2: blind analysis - bifurcation

Step 1: Background isolation

Step 2: Suppress each background with two independent cuts



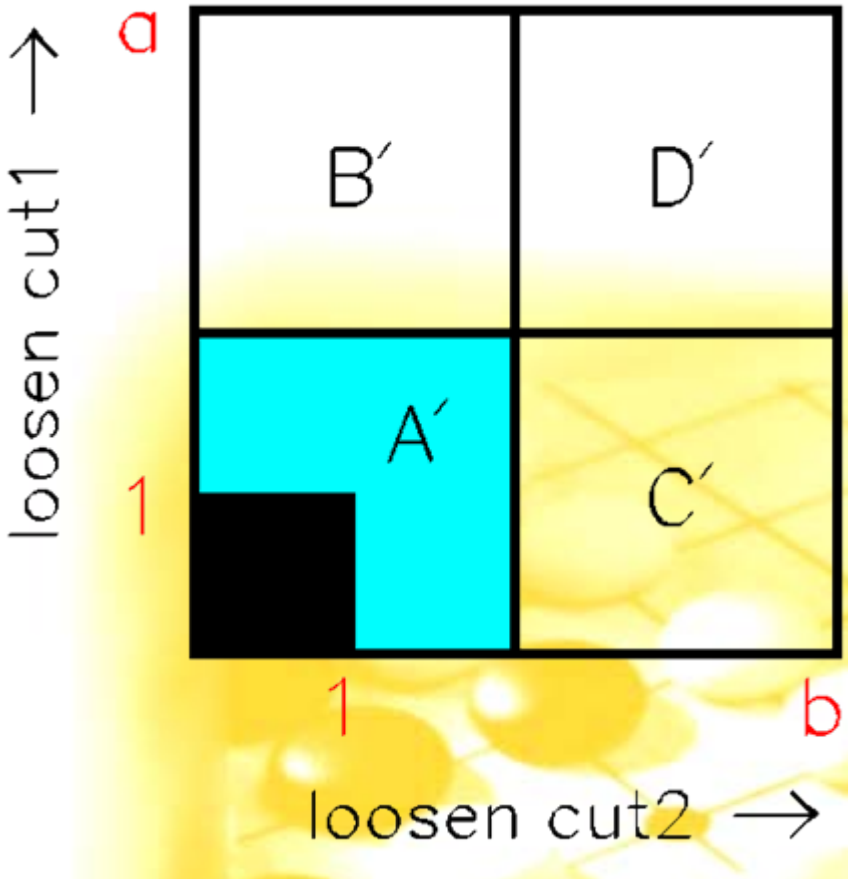
if cut1,cut2 uncorrelated,

$$A/B = C/D$$

$$A = BC/D$$

Strategy 2: blind analysis - bifurcation

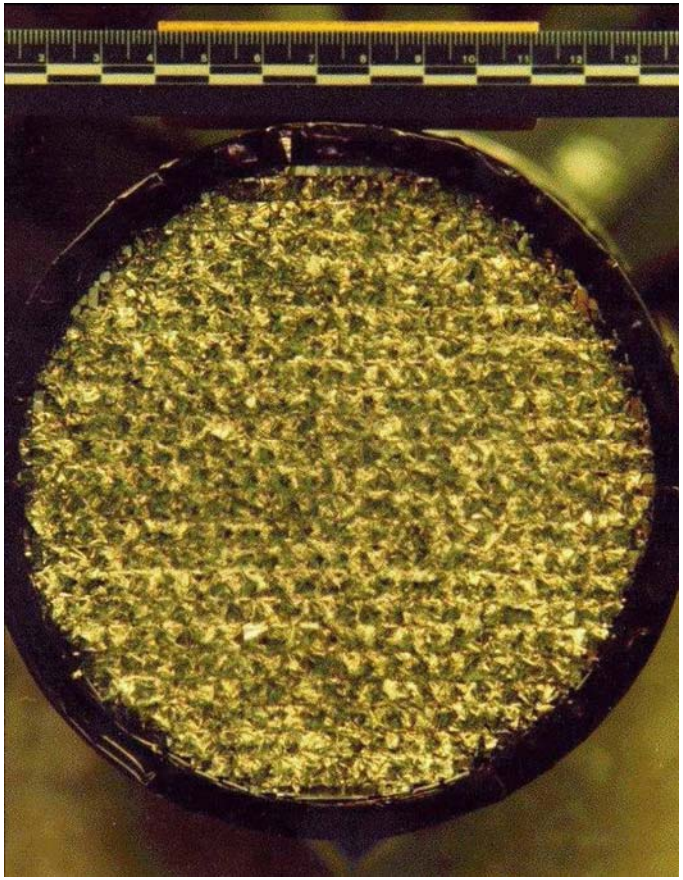
Step 3: Check the correlation

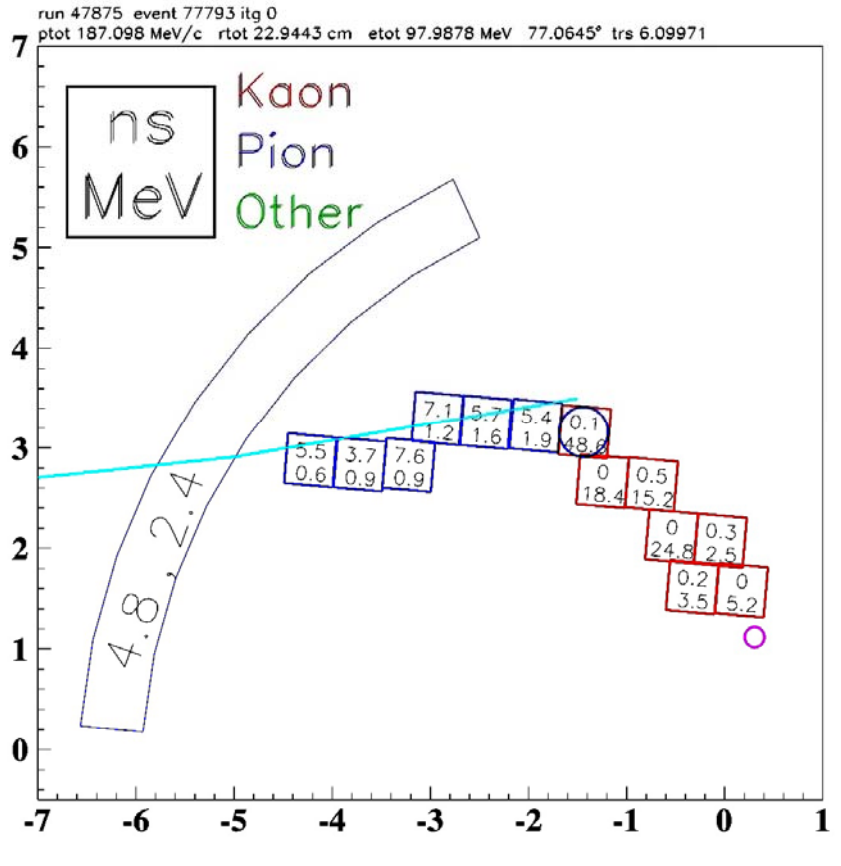


$$bg' = bg(A') - bg(A) = B'C'/D' - BC/D$$

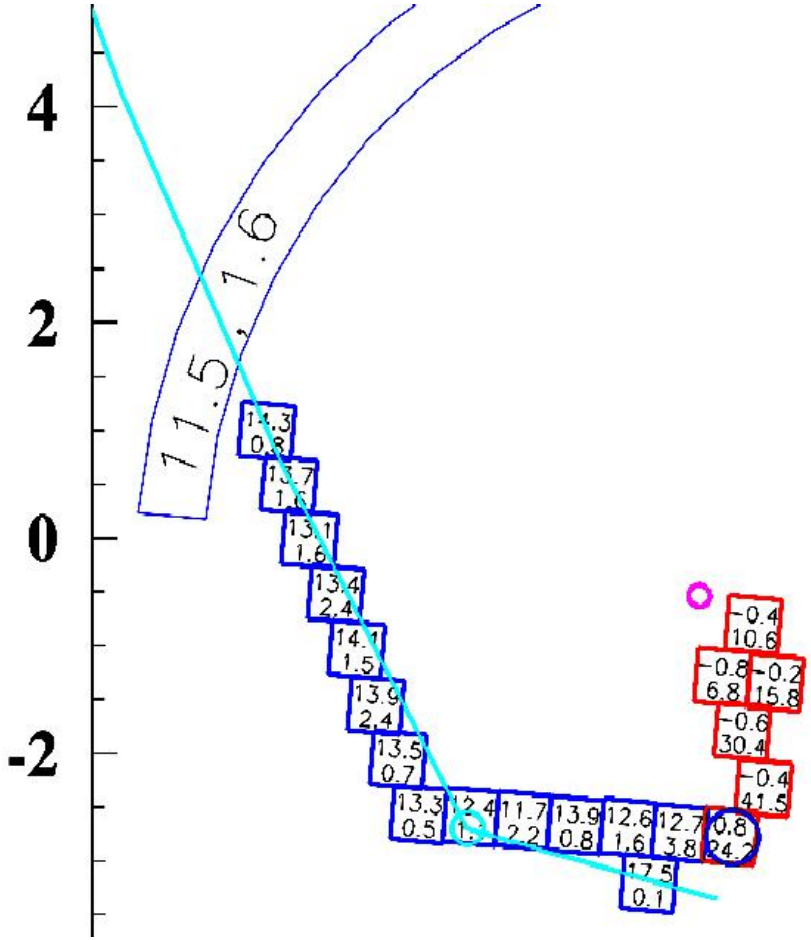
$K^+ \to \pi^+\pi^0$ target scattering background

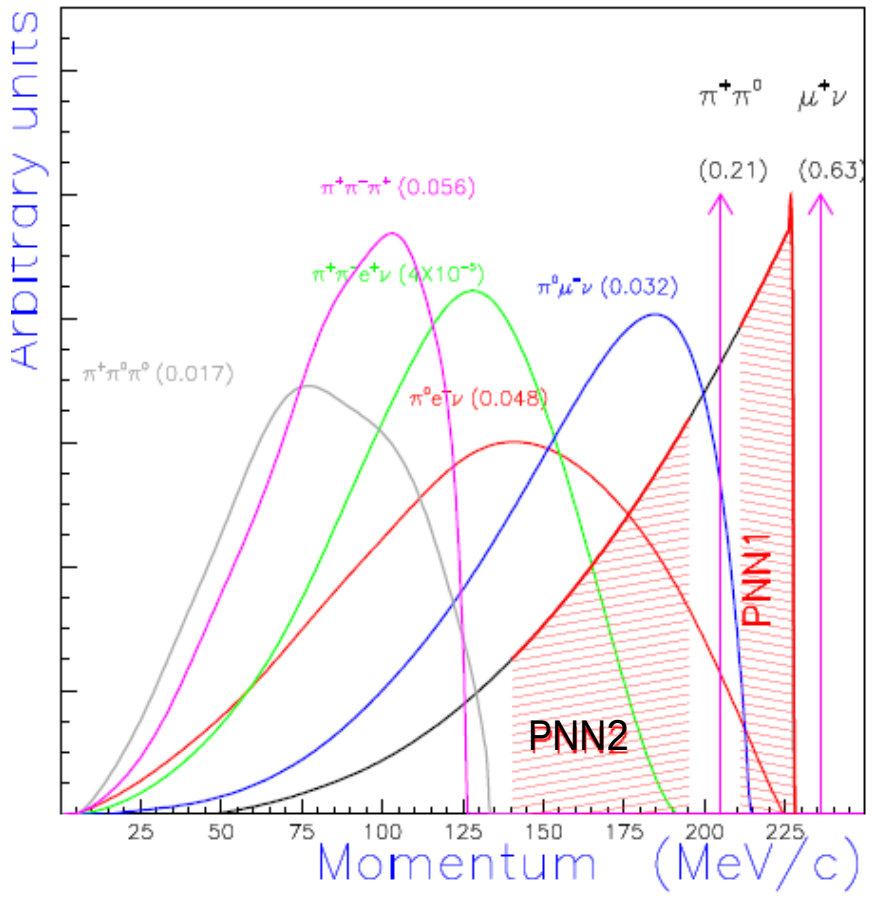
Typical pattern in target:





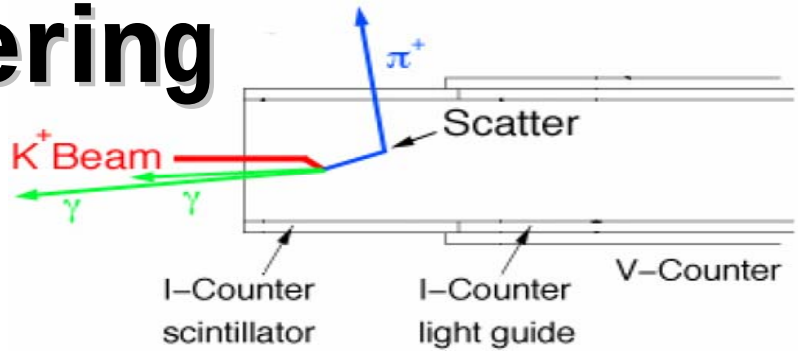
Transversal Scattering

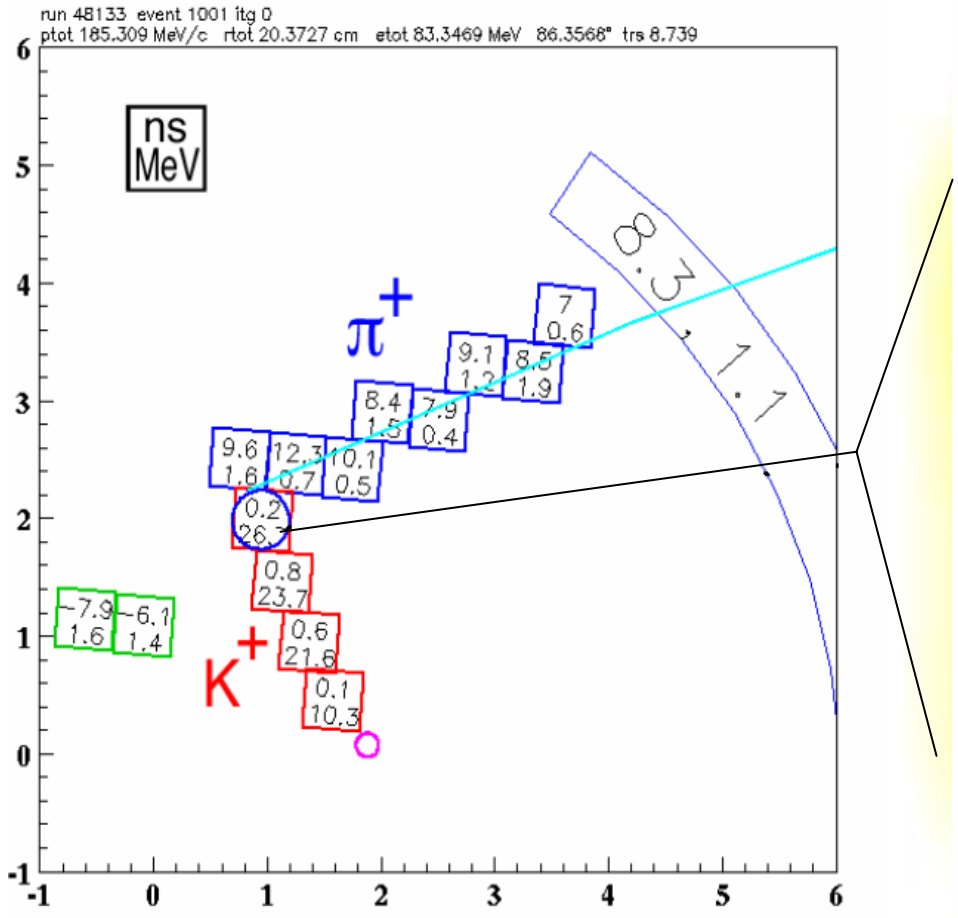


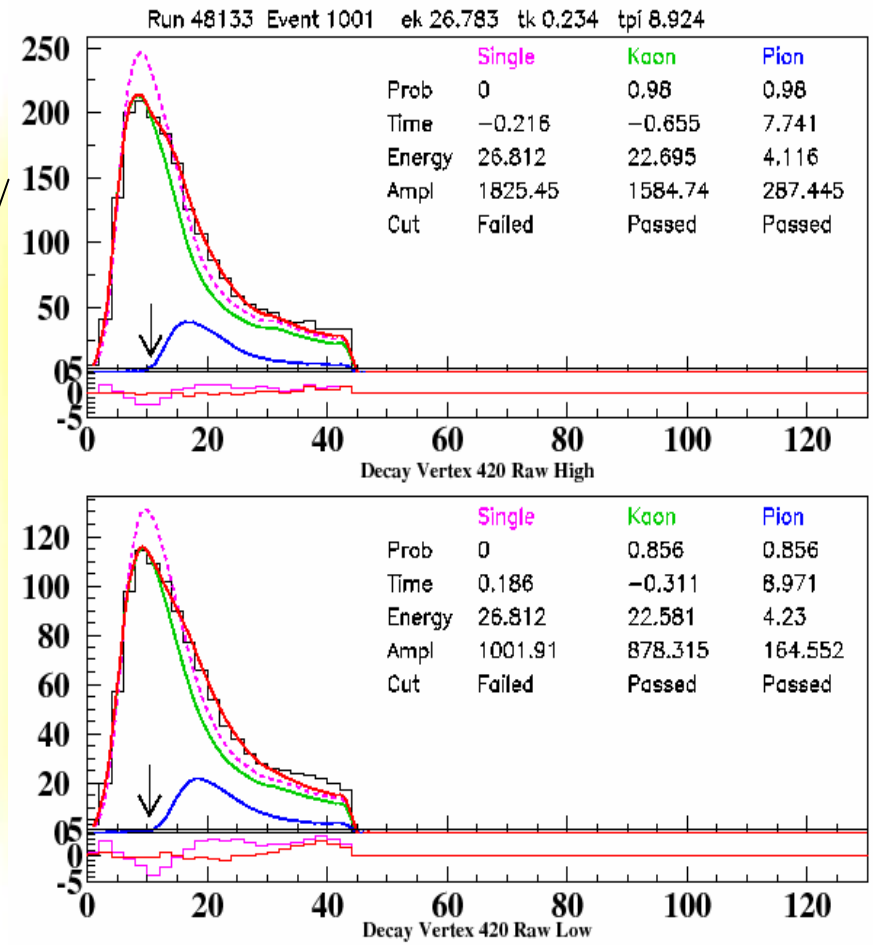


Longitudinal scattering

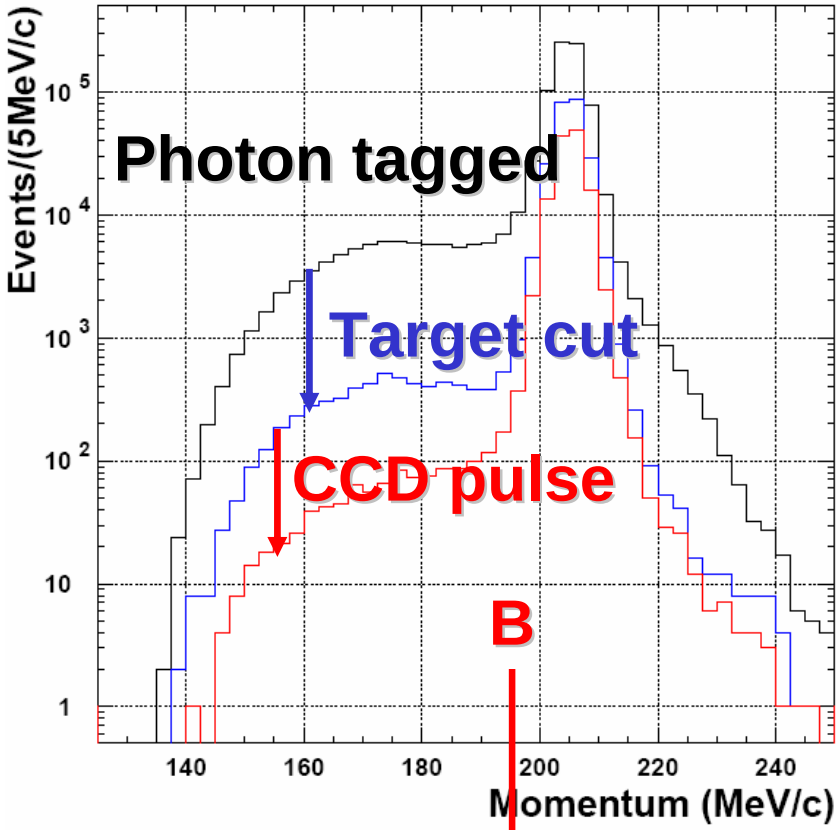
CCD pulse cut

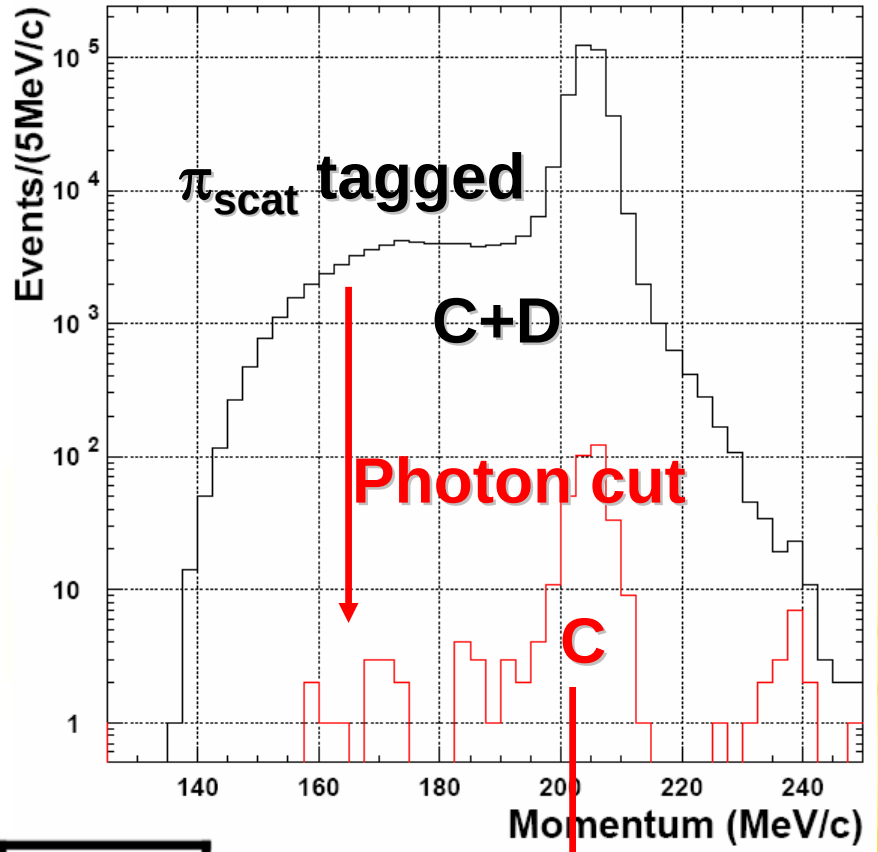


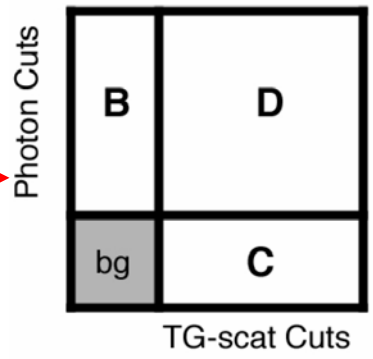




Measure $K^+ \to \pi^+\pi^0$ background

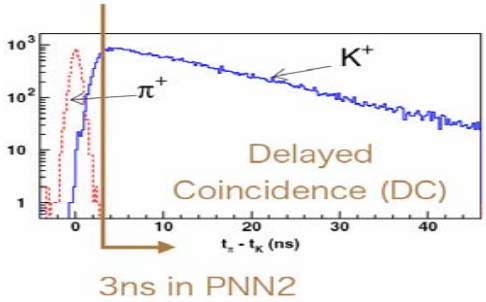


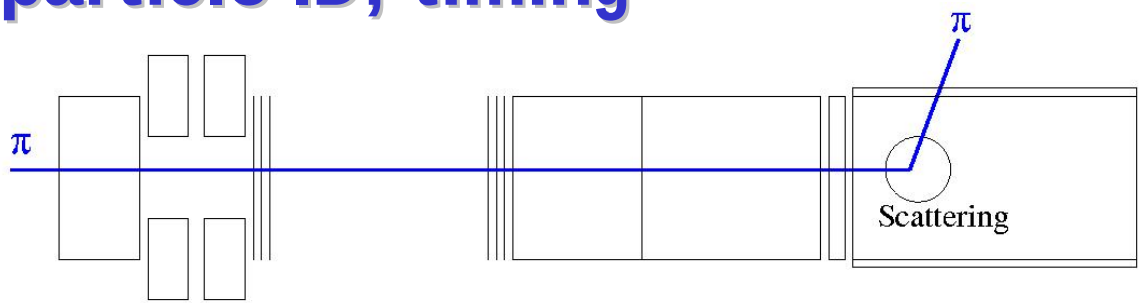




Beam background

- **Single beam: particle ID, timing**

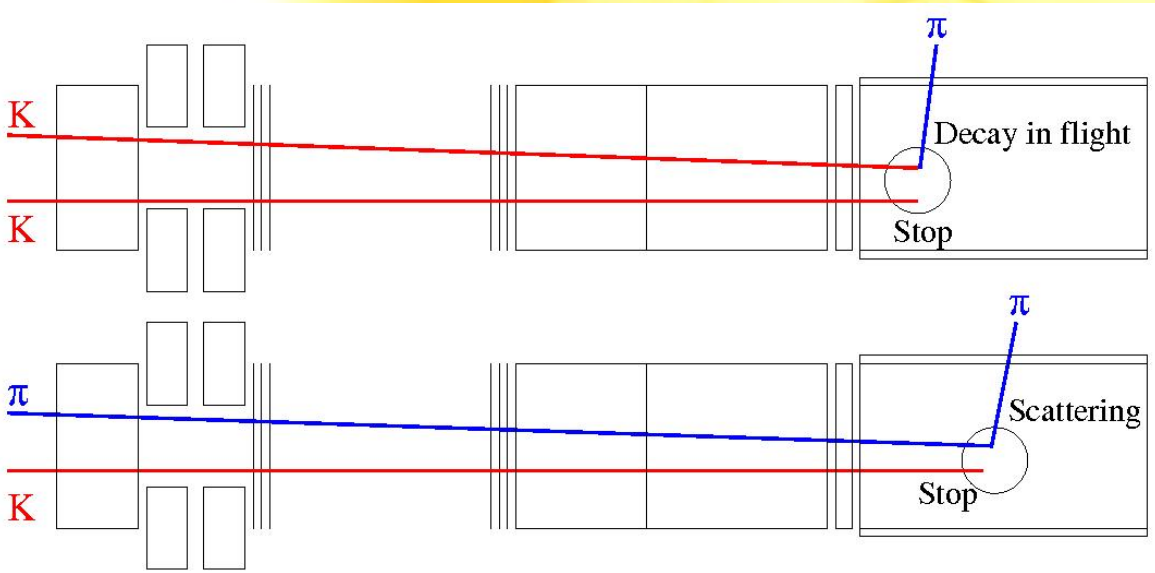




- **Double beam:**

  redundant particle ID along beam line

  - **Cerenkov**
  - **Wire chamber**
  - **Target**
  - **B4**
  - **AD**

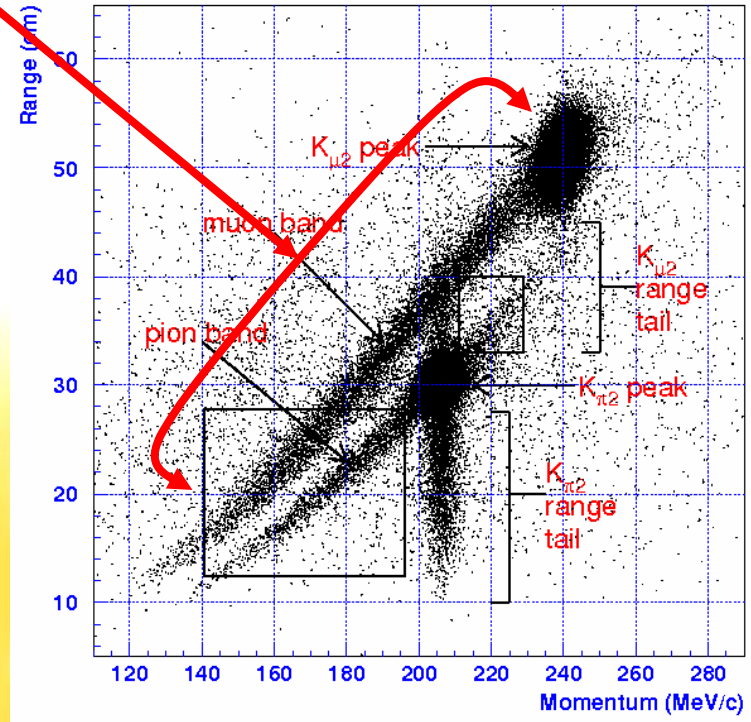


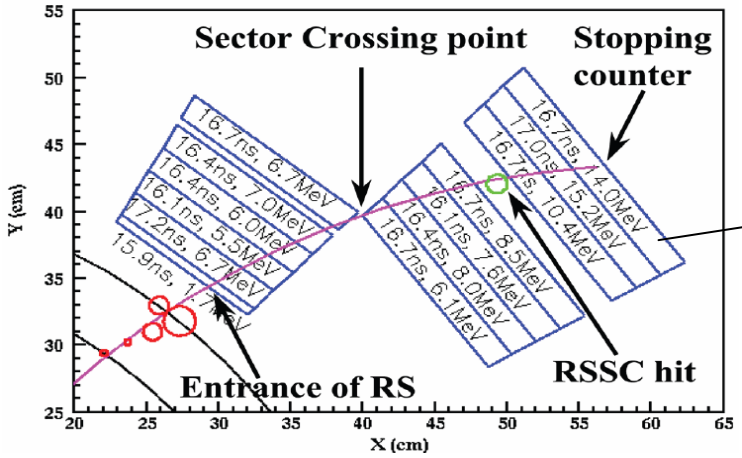
Muon background

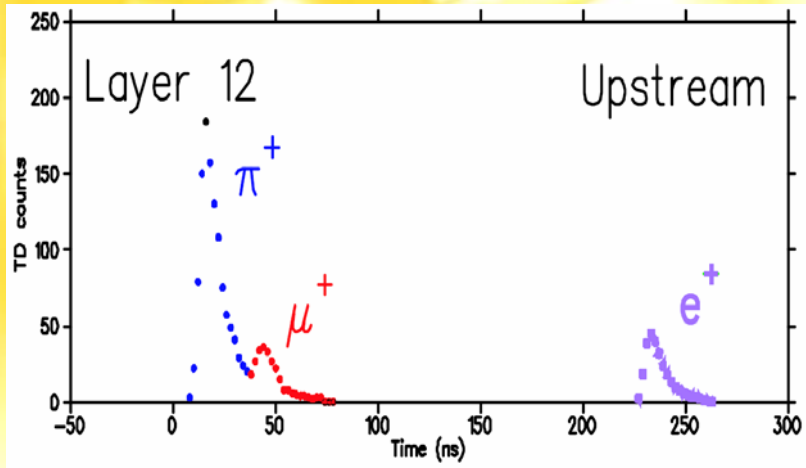
$K^+ \to \mu^+ \nu\gamma$

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

- Range momentum
- dE/dx range stack
- $\pi \to \mu \to e$ chain



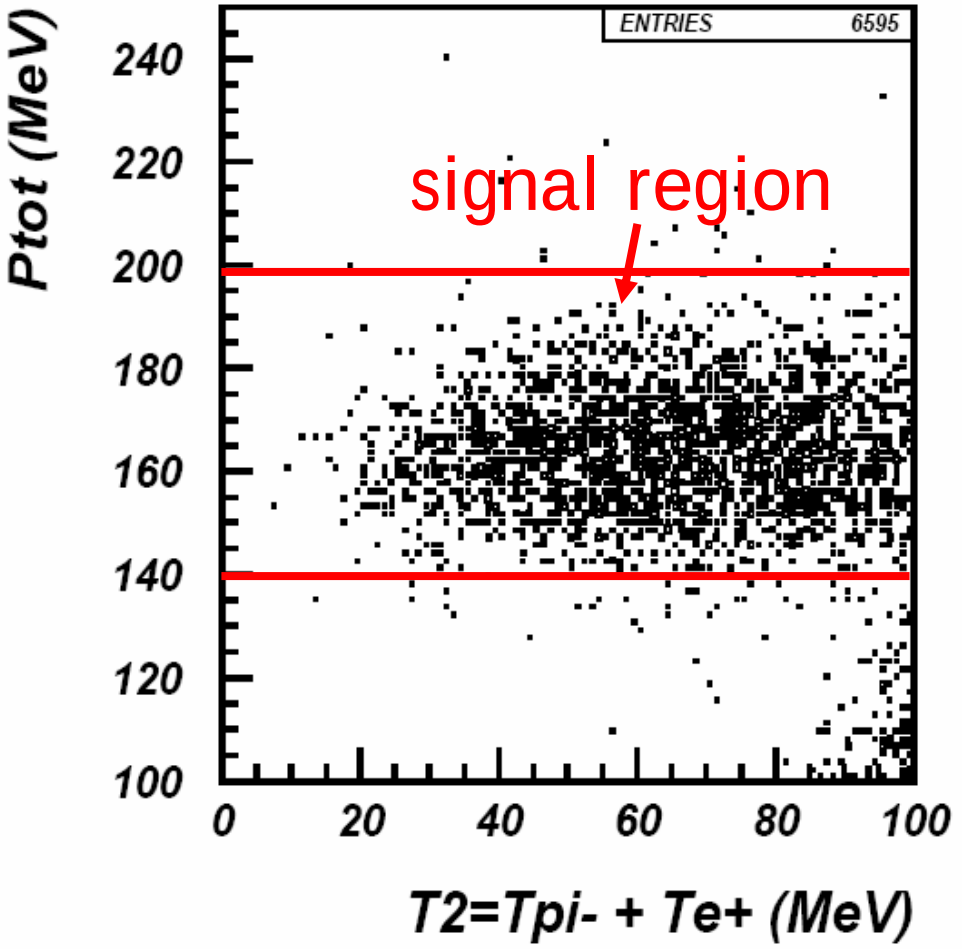




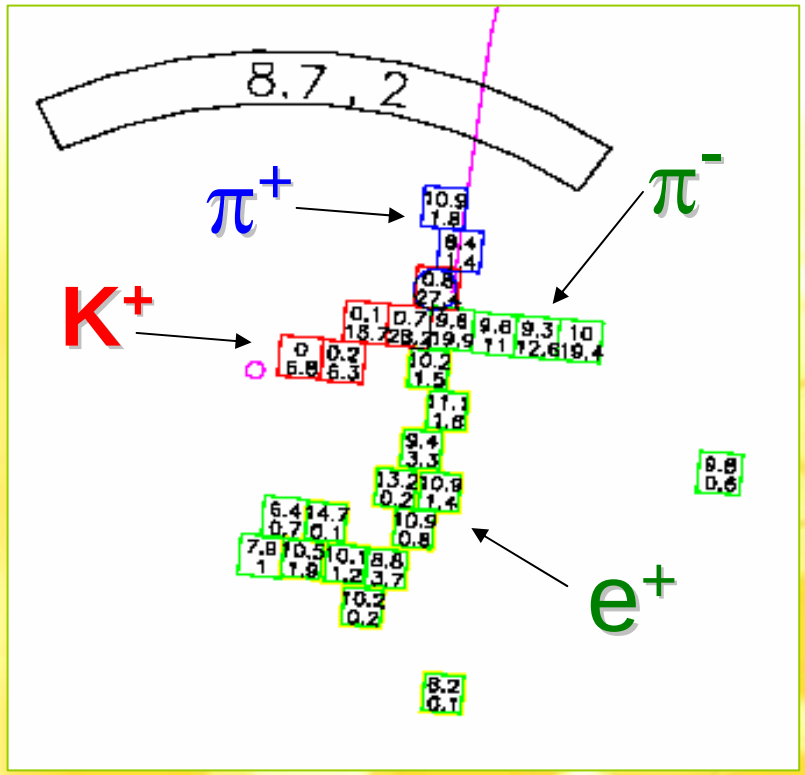
Ke4 ($K^+ \to \pi^+ \pi^- e^+ \nu$) background

Their energy could be very low

Ke4 MC event

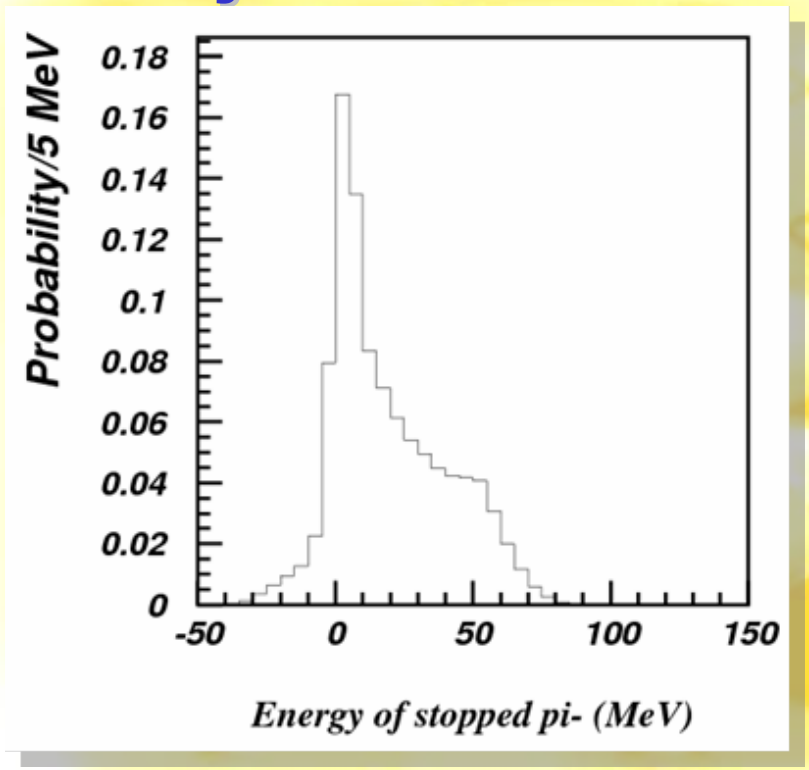


A Ke4 candidate from data



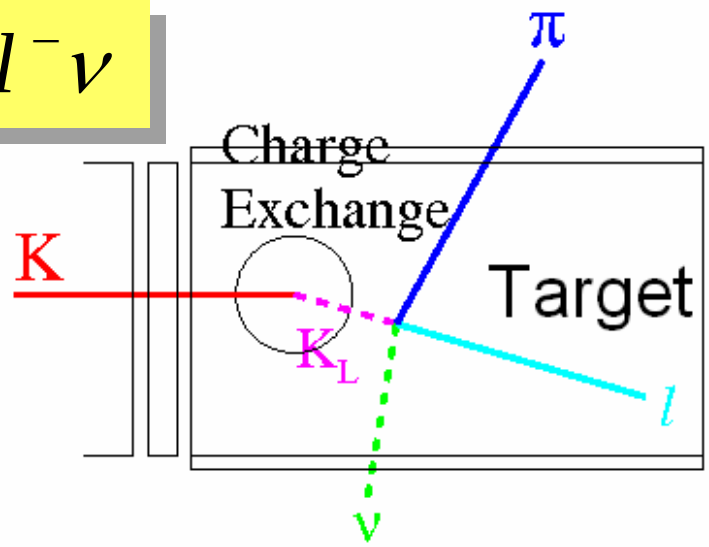
Ke4 ($K^+ \to \pi^+\pi^-e^+\nu$) background

- A Ke4-rich sample is tagged in data by selecting events with extra energy in target.
- Use MC to evaluate the rejection of cuts
- The π^- annihilation energy spectrum is from our experimental measurement



Charge exchange ($K^+n \rightarrow K^0p$) background

$$K^+ n \rightarrow K^0 p, \quad K_L^0 \rightarrow \pi^+ l^- \nu$$



Character:

- a gap between K^+ and π^+
- z info of π^+ is not consistent with K^+ track

- A CEX rich sample is tagged in data by selecting events with a gap between K^+ and π^+
- Model K_L momentum from K_S monitor sample
- Use MC to evaluate the rejection

Single/double cut(s) failure study
-- look for a loophole

- Usually introduce a cut or a group of cuts aiming at a background
- By inverting the cut(s) the background is selected
- The number of events and their characteristic can be predicted
- If observation is not consistent with prediction a new background is found or your cuts are not complete

Acceptance measurement

- Accidental hits and noise will bias acceptance measurement, so data (monitor sample) is used.

  example:

  Acc loss of photon veto cut on $K^+ \to \mu\nu$

  No photon in the final state of $K^+ \to \pi^+\nu\nu$

  Acc of photon veto is measured with $K^+ \to \mu\nu$

- MC is only used to measure the acceptance of kinematics box cuts and detector solid angle

- BR($K^+ \to \pi^+\pi^0$) is measured to validate acceptance measurement

Total background and sensitivity

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}

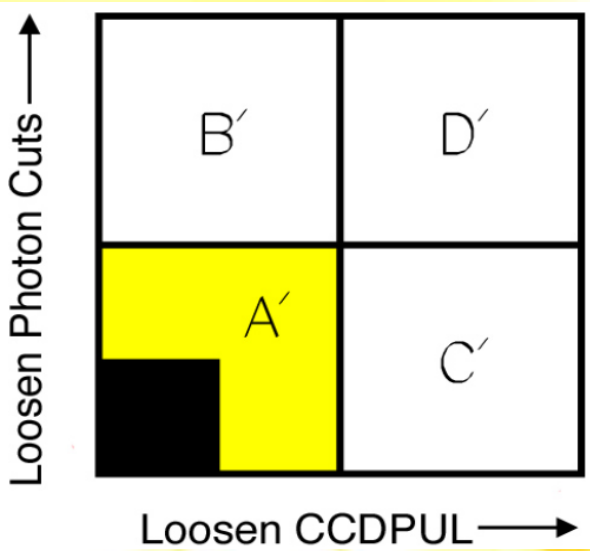
For E787+E949 pnn1 SES=0.63×10^{-10}

SES is the branching ratio for a single event observed w/o background

Outside box study

- Keep signal region blinded
- Relax photon veto or ccd pulse cut
- Check the predicted events and observed events in the extended region A'

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



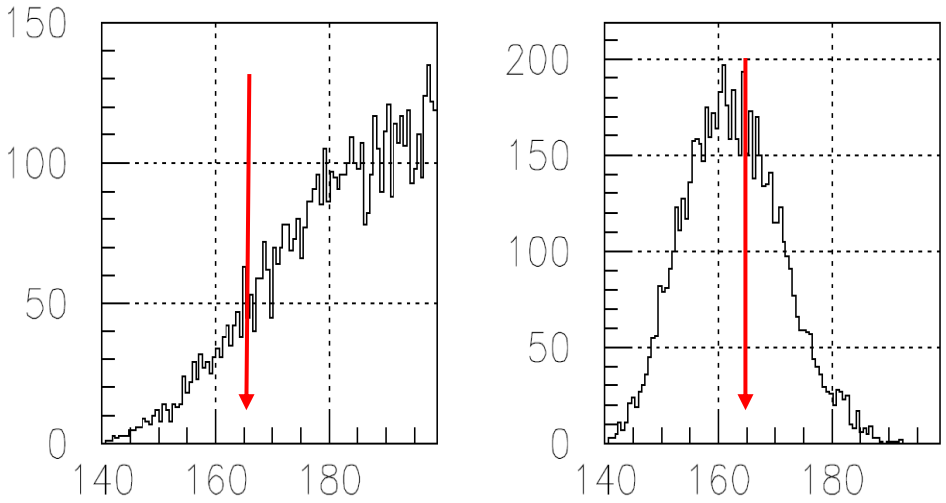
The probability to observe ≤ 3 events when $9.09^{+1.53}_{-1.32}$ are expected is 2%. The probability of the observation in regions CCD_1 and PV_1 given the expectation is 5%; the expectation is [2%,14%] when the uncertainty in $N_{\rm exp}$ is taken into account.

Division of signal region – We know more about cuts

- Acceptance and background is not uniformly distributed in the signal region
- A candidate in a cleaner region is less likely to be background

Momentum (MeV/c) of:

Signal $K^+ \to \pi^+\pi^-e^+\nu$



Lower box of p (MeV/c):

p>140

Tight p box:

p>165

Cell information – 9 cells

Acc =
0.137%

Four cuts are tightened to define 9 cells

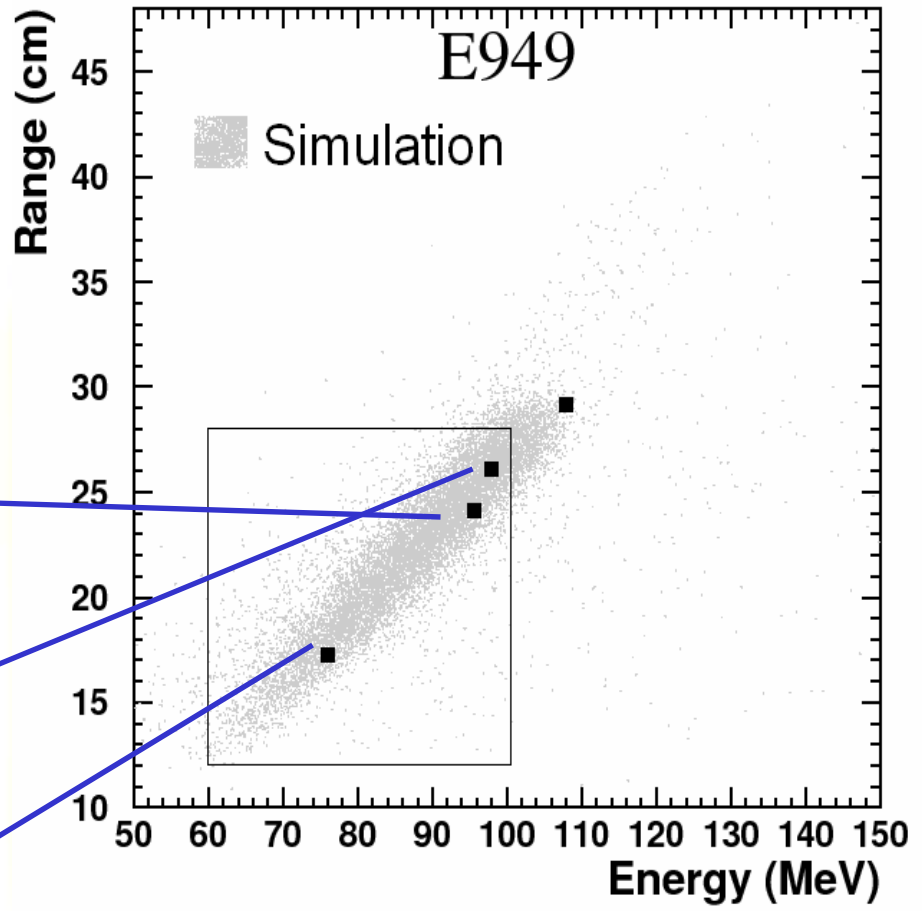
- **Kinematics box**
- **Photon veto**
- **$\pi \rightarrow \mu \rightarrow e$**
- **timing (delay coincidence)**

	rel. Acc	bkg	Acc/bkg
	0.314	0.152	2.065
	0.073	0.038	1.921
	0.031	0.019	1.653
	0.007	0.005	1.559
	0.287	0.243	1.183
	0.066	0.059	1.135
	0.028	0.027	1.036
	0.006	0.007	0.998
	0.188	0.379	0.496
sum	1	0.93	

Three candidates are found

The nine cells

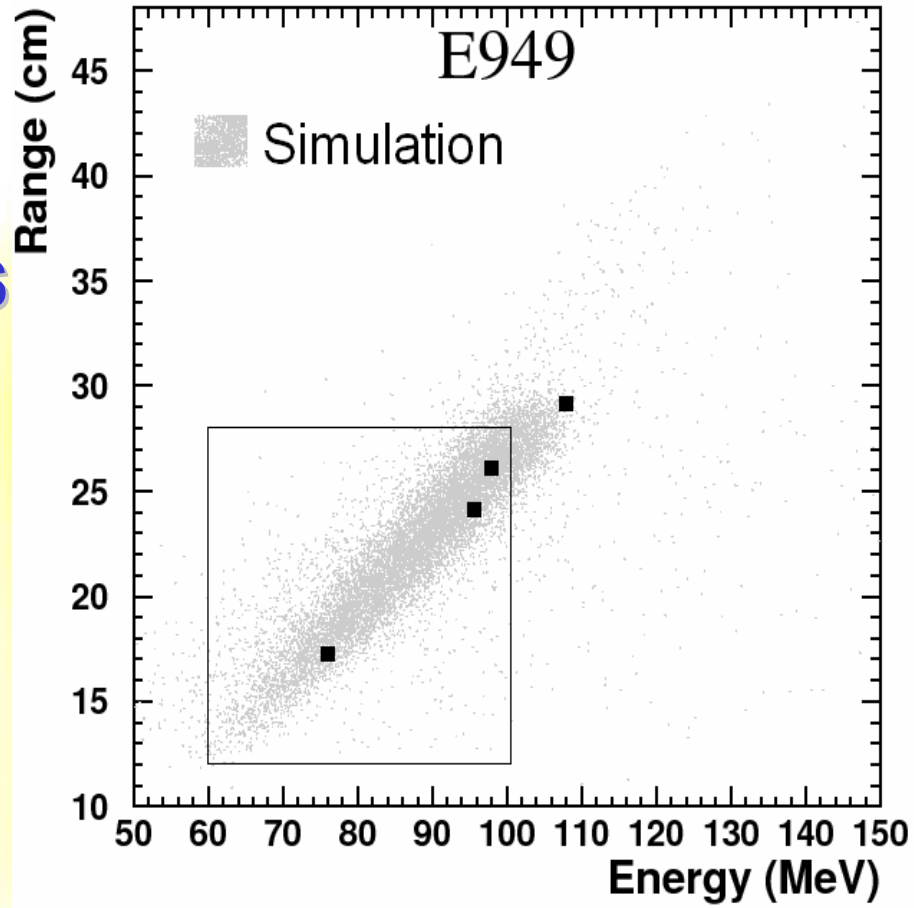
Bkgd	Events	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20



Measured $K^+ \to \pi^+ \nu\bar{\nu}$ BR of this analysis

- BR=$(7.89 \pm^{9.26}_{5.10}) \times 10^{-10}$
- The probability of all 3 events to be due to background alone is 0.037
- due to signal of SM prediction and background is 0.056
- SM prediction:

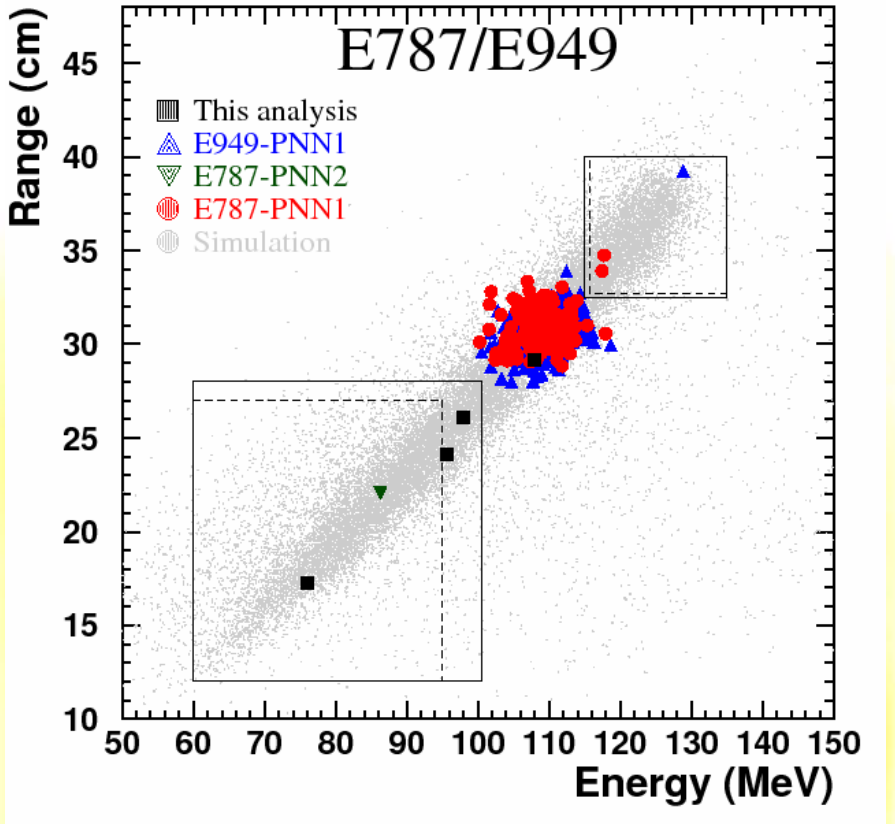
BR=$(0.85 \pm 0.07) \times 10^{-10}$



Combined with all E787/E949 result

- $BR=(1.73\pm^{1.15}_{1.05})\times10^{-10}$
- The probability of all 7 events to be due to background alone is 0.001
- due to signal of SM prediction and background is 0.06
- SM prediction:

$BR=(0.85\pm0.07)\times10^{-10}$

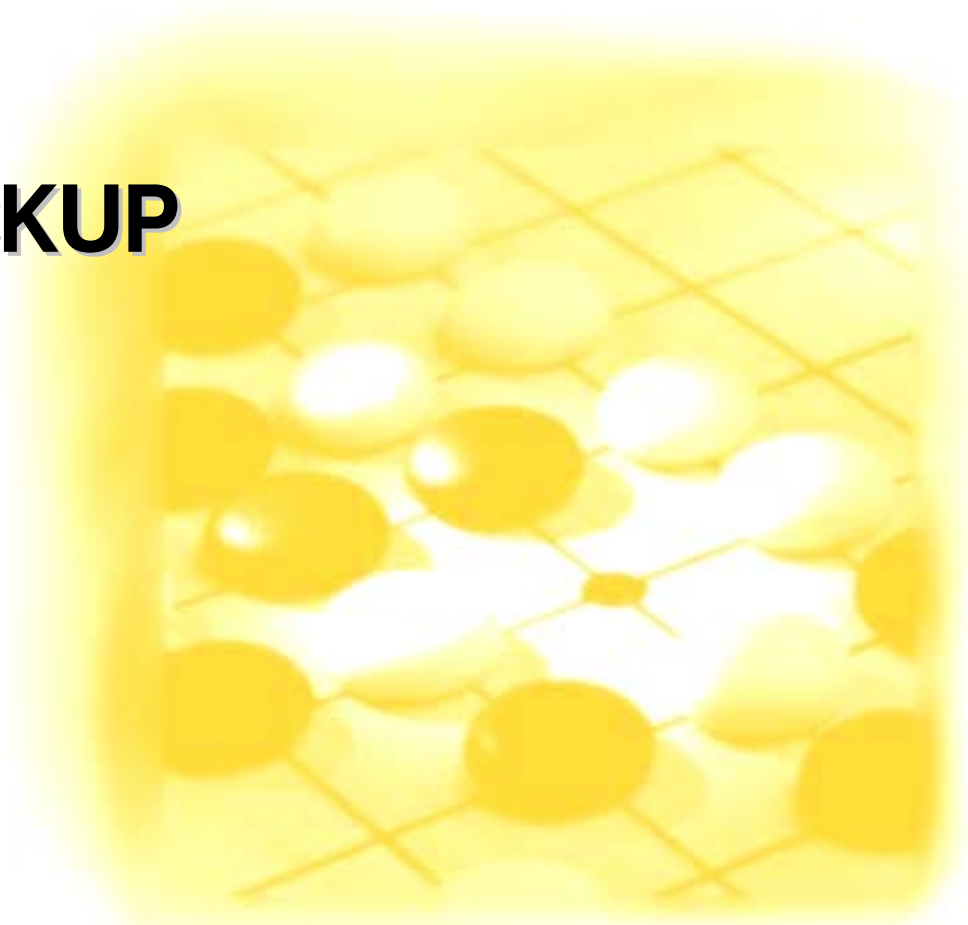


Conclusion

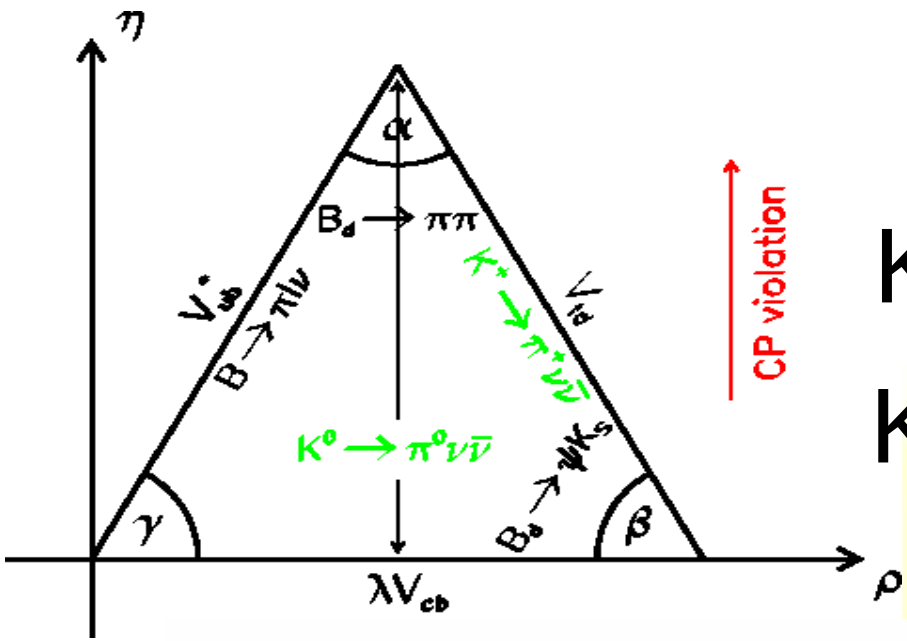
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73 \pm^{1.15}_{1.05}) \times 10^{-10}$
- Our measurement is twice of standard model prediction, however consistent with it within uncertainty
- E787/E949 made tremendous progress on rare K decay study
  - 25 years ago only a limit $<1.4 \times 10^{-7}$
  - Found 3 candidates in this study
  - (7 candidates totally)
  - arXiv:hep-ex/0808.2459 has been accepted by PRL for publication.

Your questions are welcome!

BACKUP



BR and ρ η



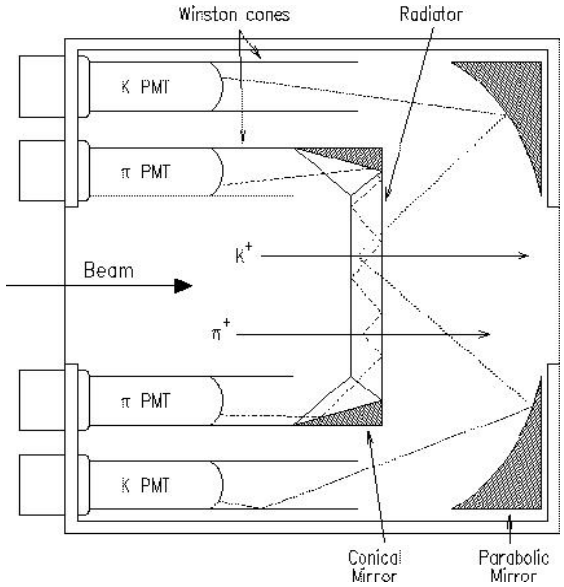
$K^+ \to \pi^+ \nu\bar{\nu}$ **E787/E949**

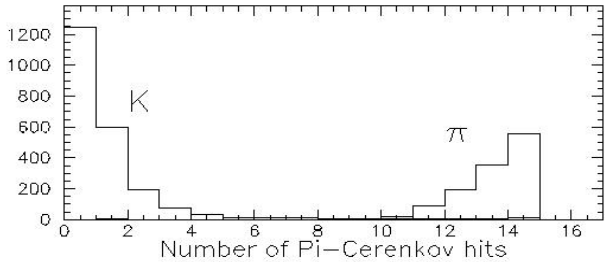
$K^0 \to \pi^0 \nu\bar{\nu}$ **E391a**

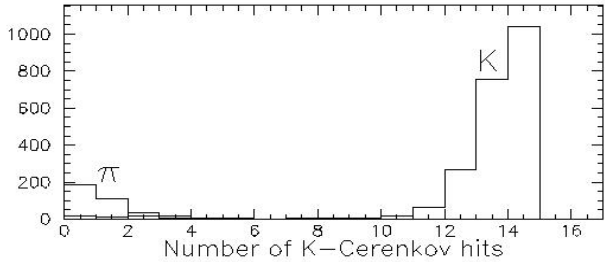
$$(\sigma\bar{\eta})^2 + (\bar{\rho} - \bar{\rho}_0)^2 = \frac{\sigma\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}{\bar{\kappa}_+ |V_{cb}|^4 X^2(x_t)}$$

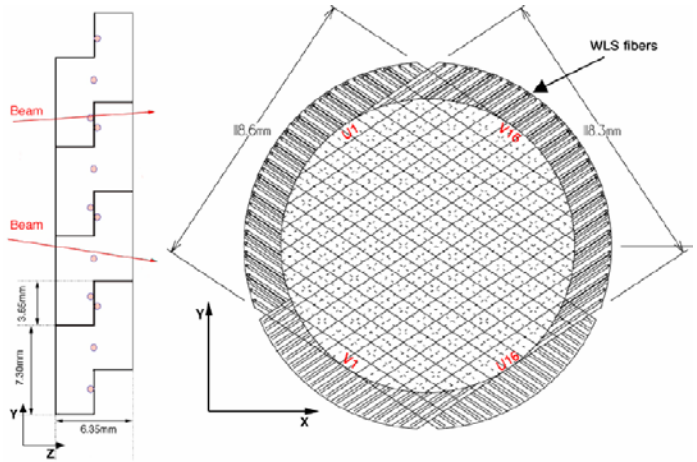
An independent measurement for CKM unitary triangle in Kaon sector

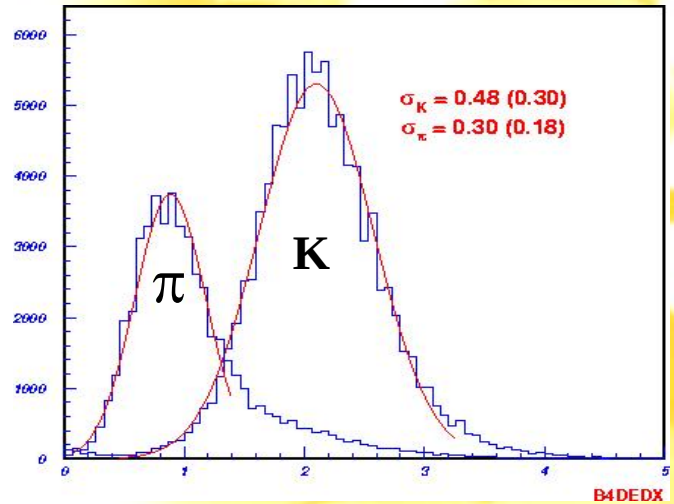
Cerenkov counter, B4







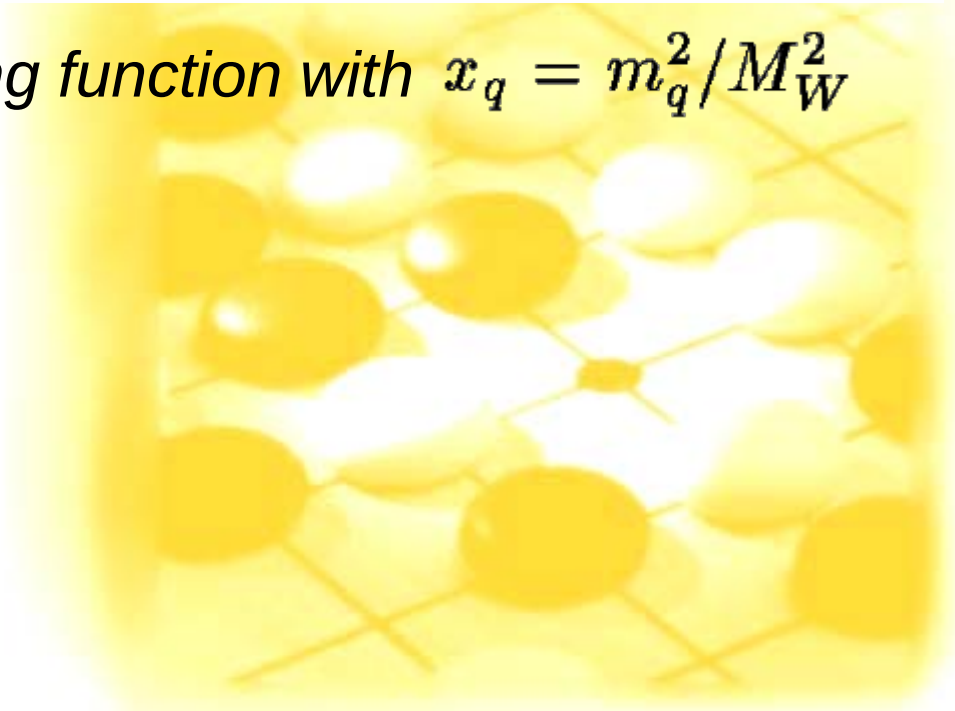




Expecting:

- Next: rare K^+ decay experiment NA62
- Next: rare K^0_L decay experiment E391a

Before isospin breaking correction:

$$\frac{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^0 e^+ \nu)} = \frac{3\alpha^2}{8\pi^2 \sin^4\theta_W} \frac{1}{|V_{us}|^2} \left| \sum_{i=u,c,t} V_{qs}^* V_{qd} X(x_q) \right|^2$$

X is a monotonically increasing function with $x_q = m_q^2/M_W^2$