$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ measurement from BNL's E949

BROOKHAVEN NATIONAL LABORATORY

$K^+ \longrightarrow \pi^+ \nu\bar{\nu}$

For the E949 collaboration:

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New Opportunities in Kaon Physics

Birmingham, UK, Nov 27 2008

Outline

- Motivation, current status of CKM measurements, the Standard Model $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ BR
- The measurement with the E949 detector
  - Background overview
  - Detector and measurement method
  - Peculiarities of the PNN2 region
- The analysis
  - Strategy and tools
  - The 2 major backgrounds
  - Cross-check methods
  - Expected background and likelihood ratio method
- The result
  - This analysis
  - Past (E787, E949 PNN1) results
  - Combined E949-E787 result

Motivation

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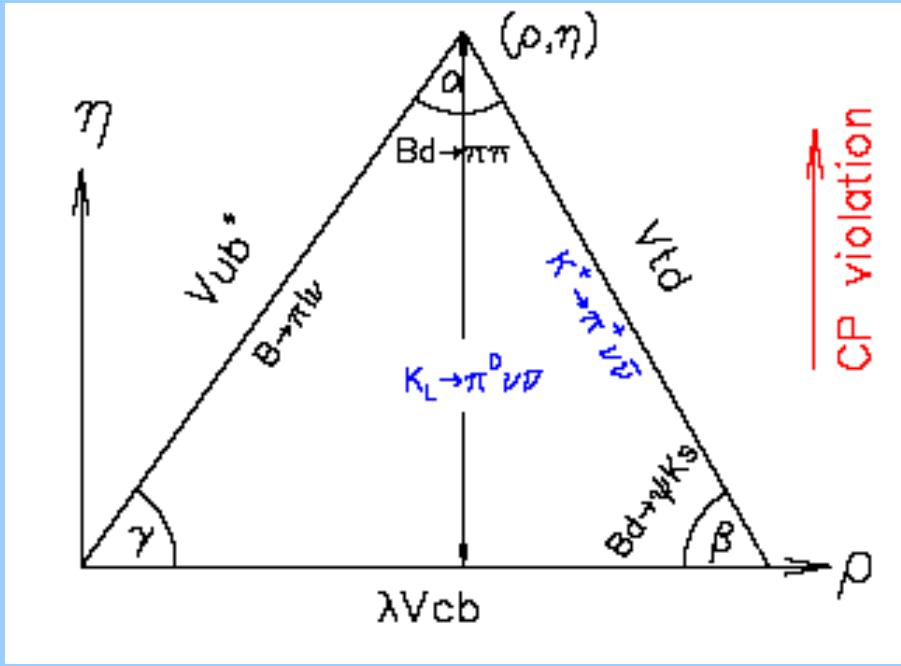
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is the rarest process ever detected in Particle Physics. It can give a direct and independent measurement of $|V_{td}|$, the smallest and most elusive element of the CKM matrix

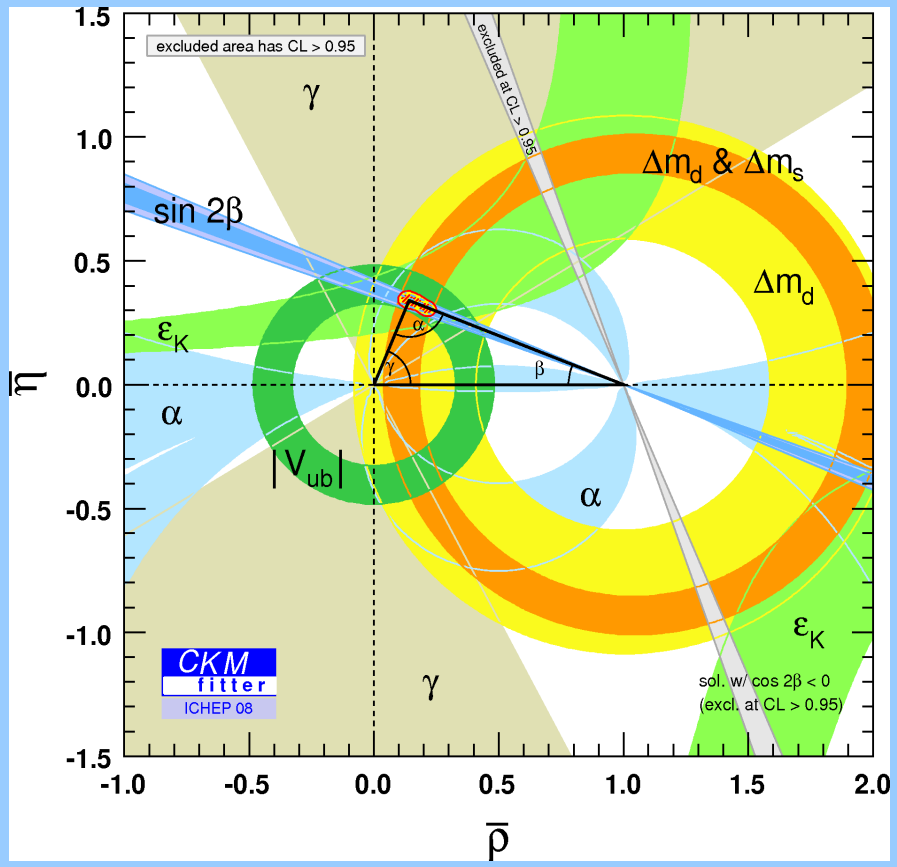
The Kaon Unitarity triangle: $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$



Processes w/ small theoretical uncertainties:

Process	Experiments
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$	E787/E949, FNAL-E921
$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu\bar{\nu})$	KOPIO, E391a
$\mathcal{A}(B \rightarrow J/\psi K_S^0)$	BaBar, Belle
CP violating decay rate asymmetry	
$\Delta M_{B_s}/\Delta M_{B_d}$	CDF, D0, LHCb, BTeV
ratio of mixing frequencies of B_s and B_d mesons	

Measurements of unitarity triangle



$|V_{ub}|, |V_{cb}|$: tree-level semileptonic B decays

$|V_{td}|$: $\Delta M_{Bs} / \Delta M_{Bd}$ & $K^+ \to \pi^+ \nu \bar{\nu}$

$\sin 2\beta$ (& 2α) : CP asymmetry in hadronic B decays $A(B_d \to J/\psi\, K_s^o)$ & $BR(K^+ \to \pi^+ \nu \bar{\nu}) / BR(K^o \to \pi^o \nu \bar{\nu})$

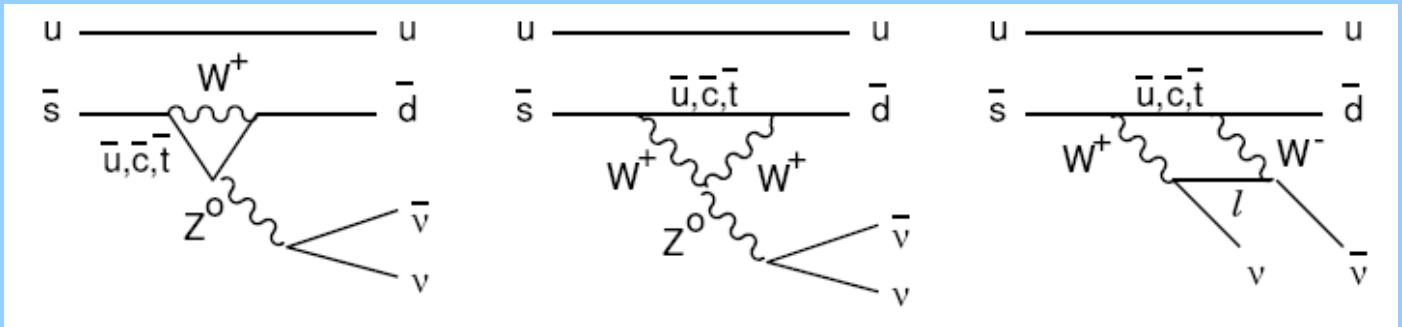
ε_K : CP violation in the K sector

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184],updated results and plots available at: http://ckmfitter.in2p3.fr

A better determination of V_{td} from $K^+ \to \pi^+ \nu \bar{\nu}$ will provide a sensitive test of the SM by comparing the results from the K and B sector and probe new physics

The SM $K^+ \to \pi^+ \nu\bar{\nu}$ BR

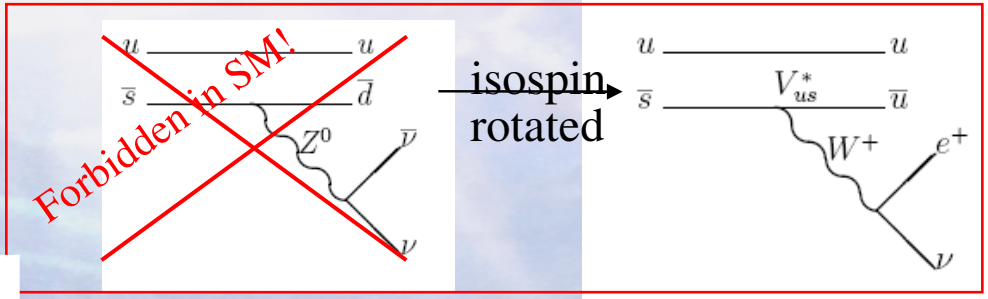
- All processes at 2nd order, with main contribution of t in the loop
- Very clean calculation (precision < 5%, uncertainties mainly from c sector)



$$BR(K^+ \to \pi^+ \nu\bar{\nu}) \propto \sum_{l=e,\mu,\tau} \left| \left[V_{cs}^* V_{cd} X(\chi_c) + V_{ts}^* V_{td} X(\chi_t) \right] \times \underbrace{(HADR)} \times (\bar{\nu}_l \nu_l) \right|^2 \Rightarrow$$

$$\ldots BR \propto (\sigma\bar{\eta})^2 + (\rho_0 - \bar{\rho})^2$$ →**ellipse in ρ-η plane**

$$\sigma = \left(\frac{1}{1 - \lambda^2/2} \right)^2$$



$$BR_{th}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.7) \times 10^{-10}$$

The E949 collaboration

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Students and post-docs in red.

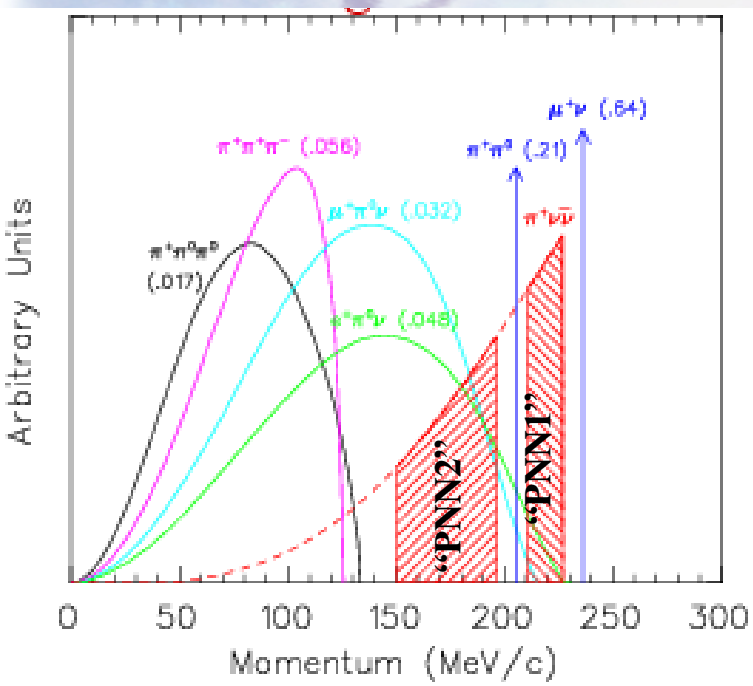
~70 physicists, plus a lot of hard work from earlier E787 collaborators.

The measurement, backgrounds

- 3-body decay w/ 2 missing particles: $0 \leq p_{\pi+} \leq 227$ MeV/c $\Rightarrow$

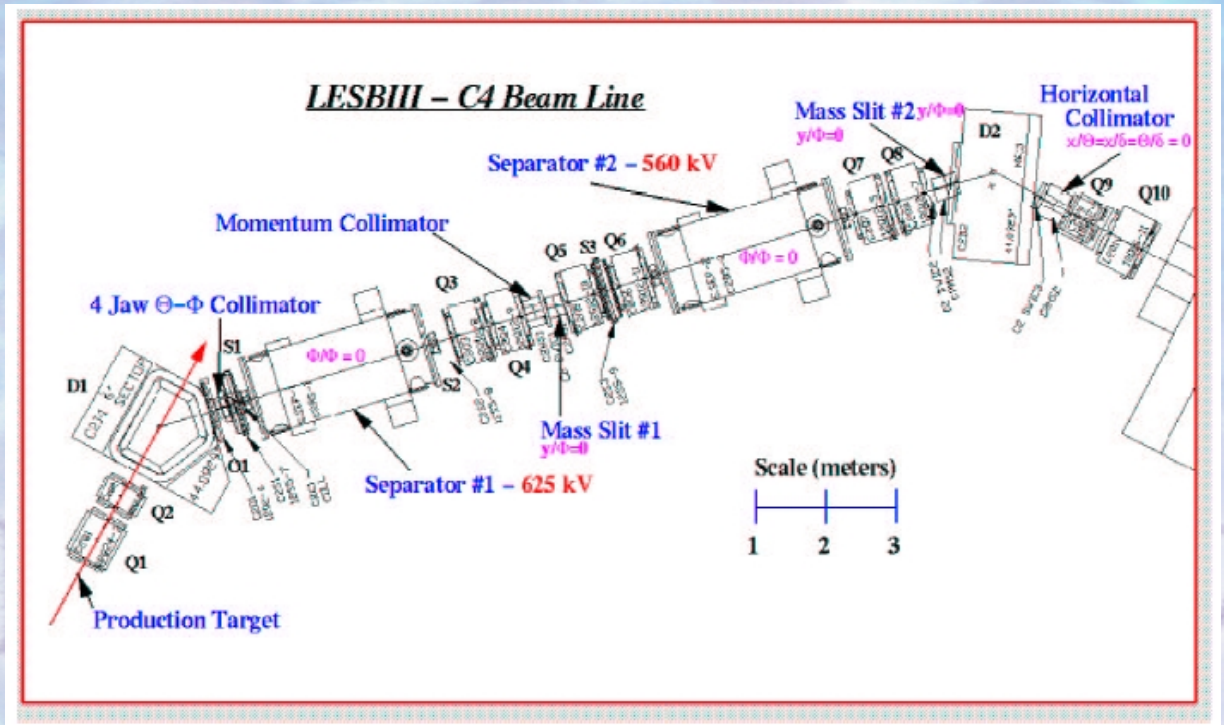
  Signal: π^+ + nothing , backgrounds need to be vetoed ~ 10^{-11} !
- Need
  - particle identification (PID)
  - all other charged particles vetoed < 10^{-3}
  - redundant precise kinematic measurements

Latest result on PNN2 will be presented



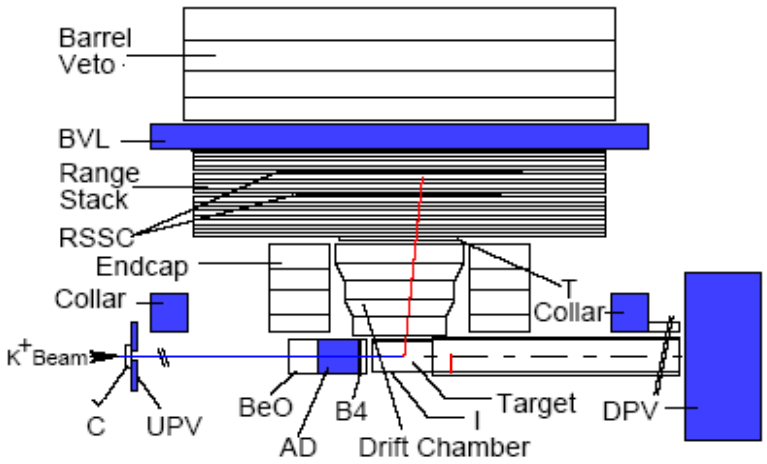
Background	BR ($\times 10^{-3}$)	Suppression method			
		PID	veto	TG	time
$K^+ \to \pi^+\pi^o$ ($K_{\pi 2}$)	209.2	-	√√	√	-
$K^+ \to \pi^+\pi^o\gamma$ ($K_{\pi 2\gamma}$)	0.275	-	√√√	-	-
$K^+ \to \pi^o\mu^+\nu$ ($K_{\mu 3}$)	33.2	√	√√	-	-
$K^+ \to \mu^+\nu\gamma$ ($K_{\mu 2\gamma}$)	6.2	√	√	-	-
$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4})	0.041	-	√	√	-
Beam backgrounds:					
single beam	-	√	-	-	√
double beam	-	-	√√	-	-
CEX: $K^+n \to K^op$	$R_{K_L} = 2.8 \times 10^{-5}$	-	√	√	(√)
$K_L^o \to \pi^+\mu^-\bar{\nu}$	135.0				
$K_L^o \to \pi^+e^-\bar{\nu}$	194.0				

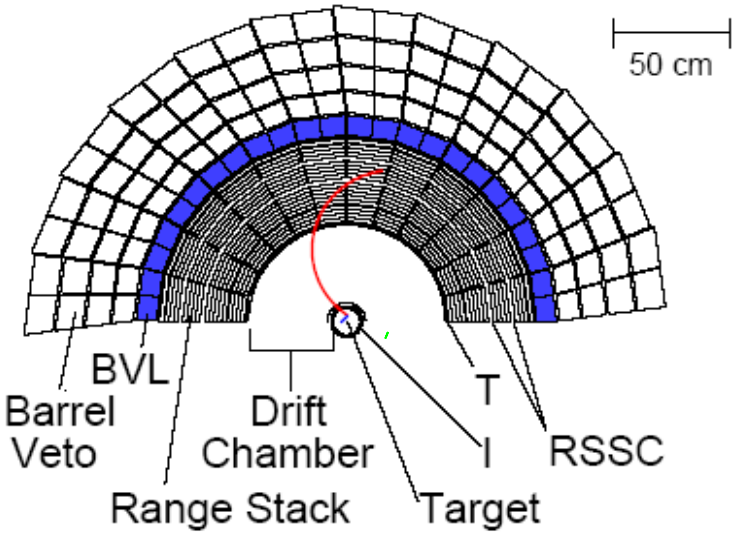
The beam



- The AGS extracts ~ 65× 10^{12} protons at 22 GeV/c over a 2.2 sec spill, every 5.4s
- They are shot on a platinum target and particles produced at ~ 0° are sent to the Low Energy Separated Beamline (LESB III), where K^+ are electrostatically separated from π^+ and focused
- Finally in the E949 target, ~ 3.5× 10^6 K^+/spill arrive and stop, with a ratio of K/π ~ 2.5-3

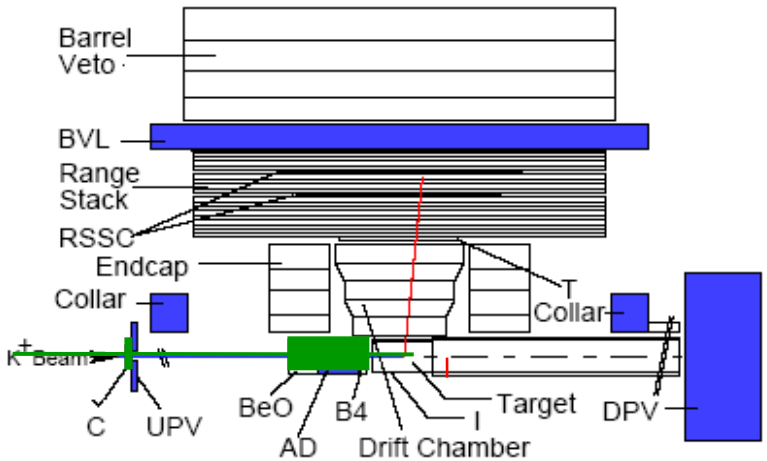
The measurement w/ E949 detector

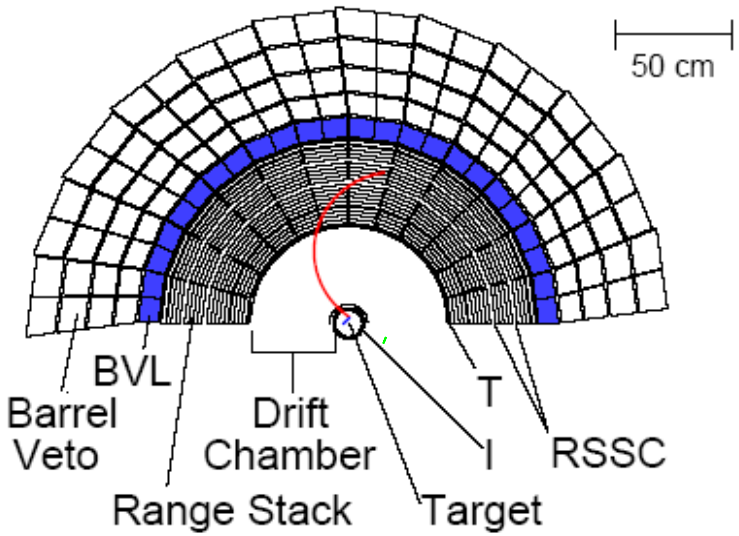




- Incoming 700MeV/c beam K^+: identified by ckov, WC, scint. hodoscope (B4). Slowed down by BeO and AD
- K^+ stops & decays at rest in scintillating fiber target – measure delay (2ns)
- Outgoing π^+ : verified by IC, VC, T counter. Momentum measured in UTC, energy & range in RS and target (1T magnetic field parallel to beam)
- π^+ stops & decays in RS – detect $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain
- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV
- New/upgraded elements

The measurement w/ E949 detector





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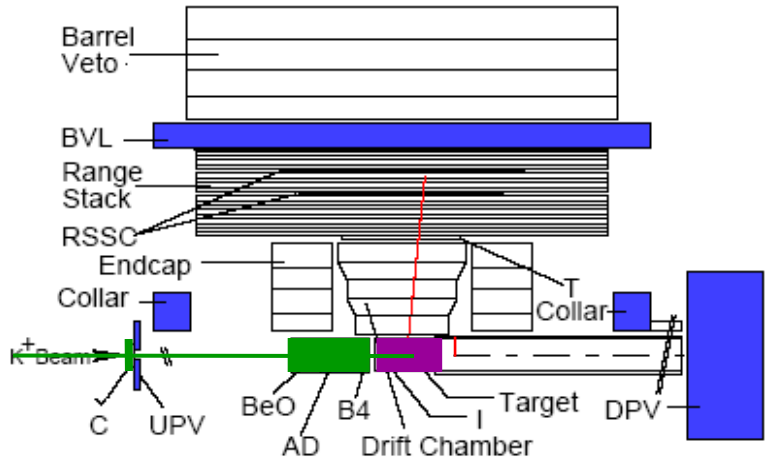

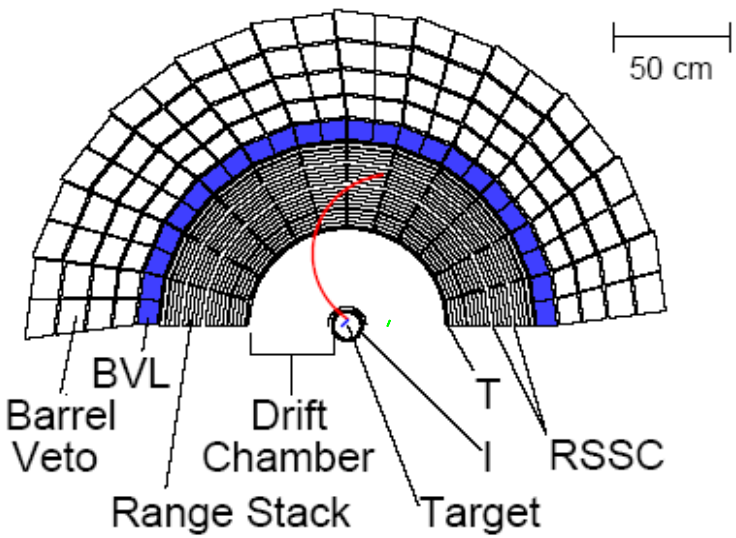

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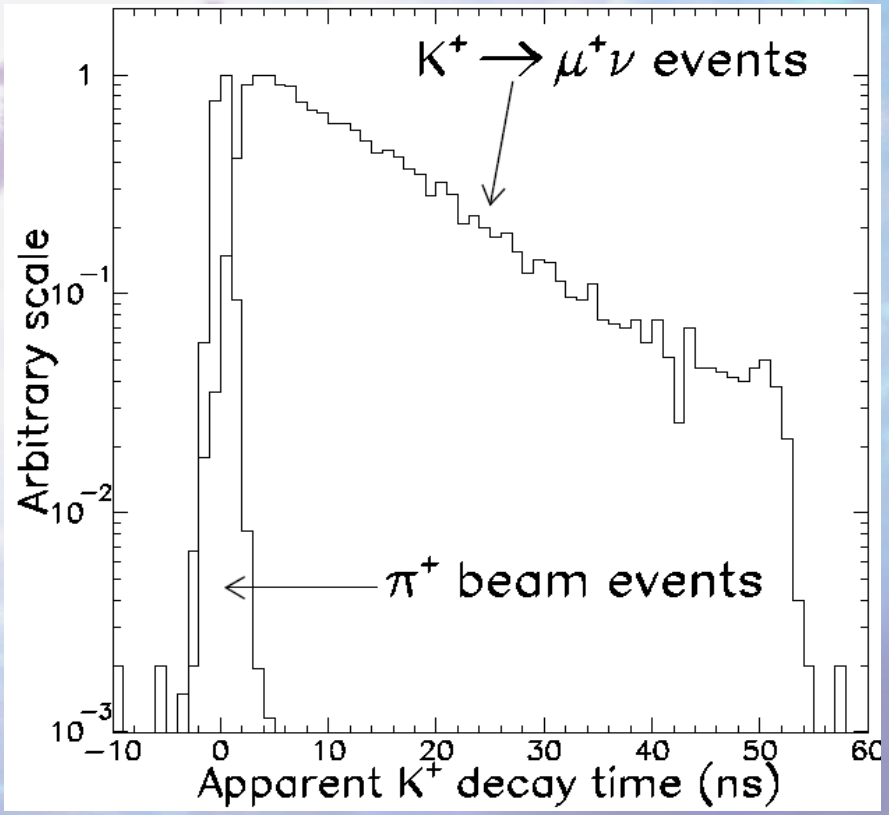

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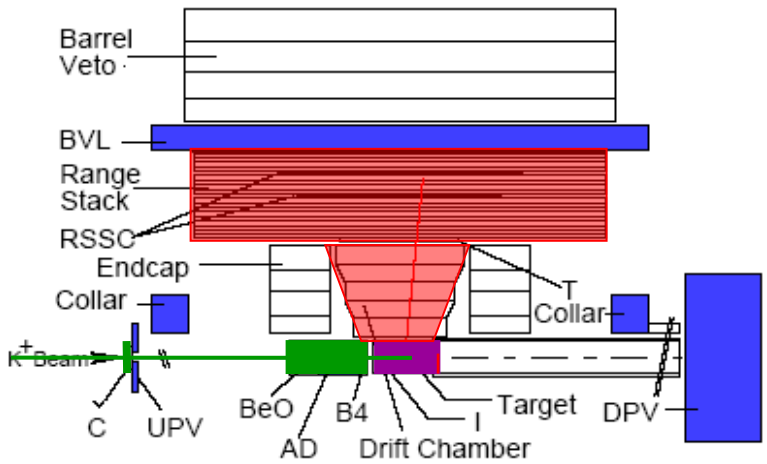

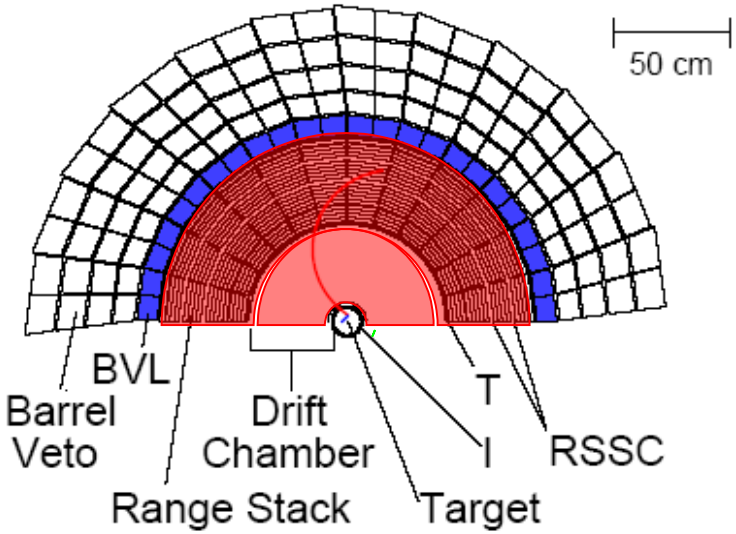

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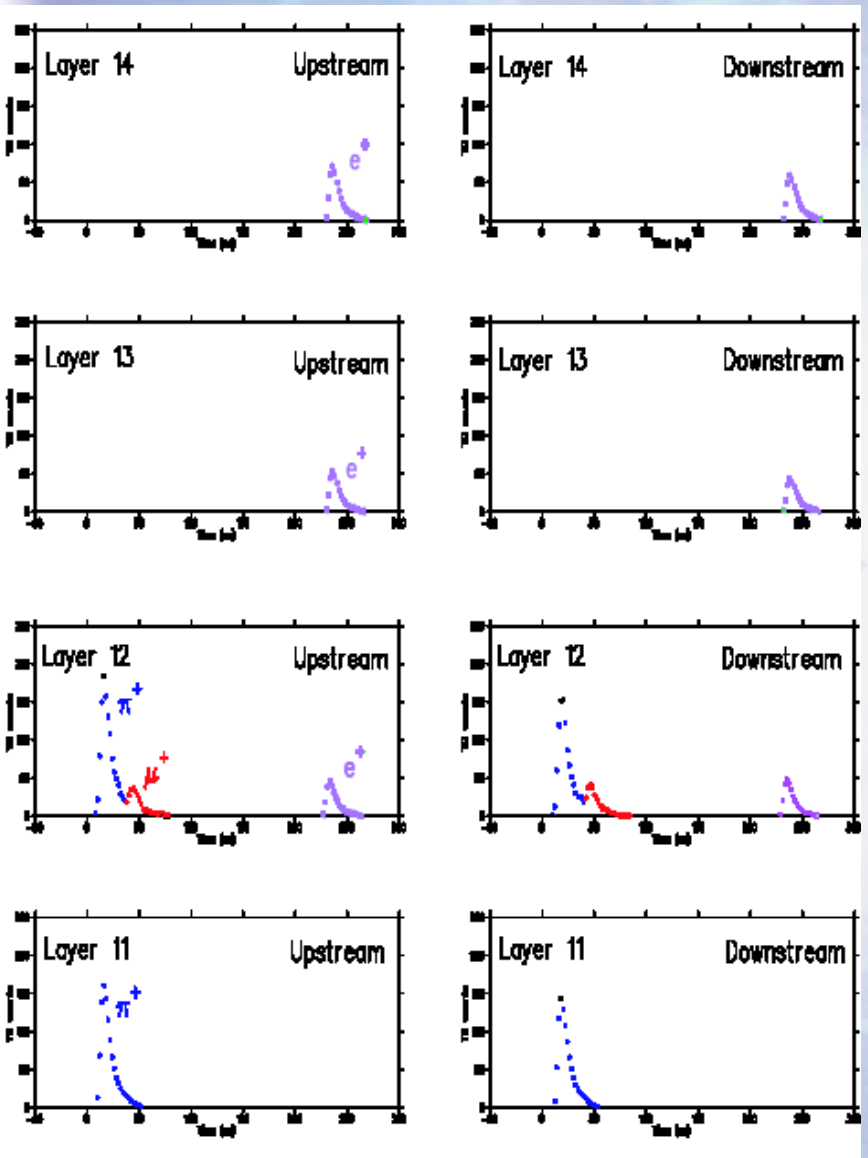
(1T magnetic field parallel to beam)

The measurement w/ E949 detector



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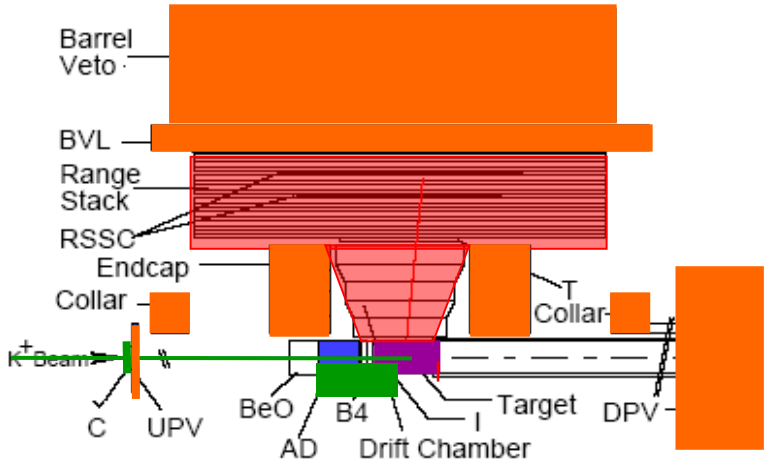

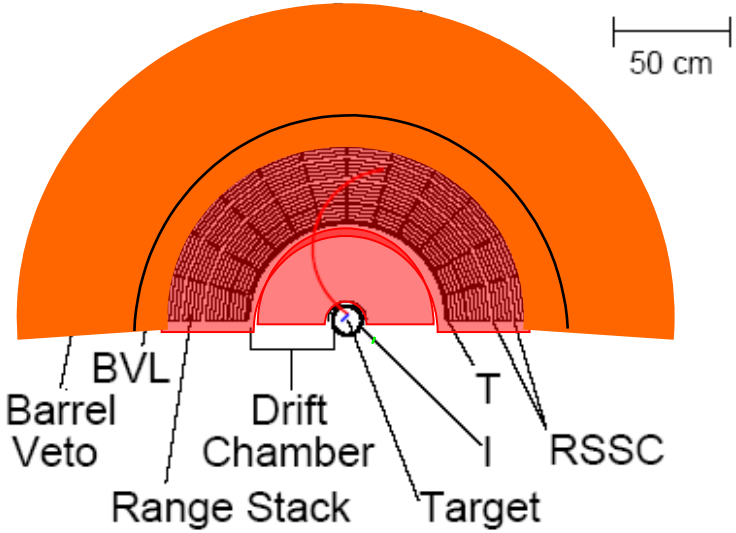

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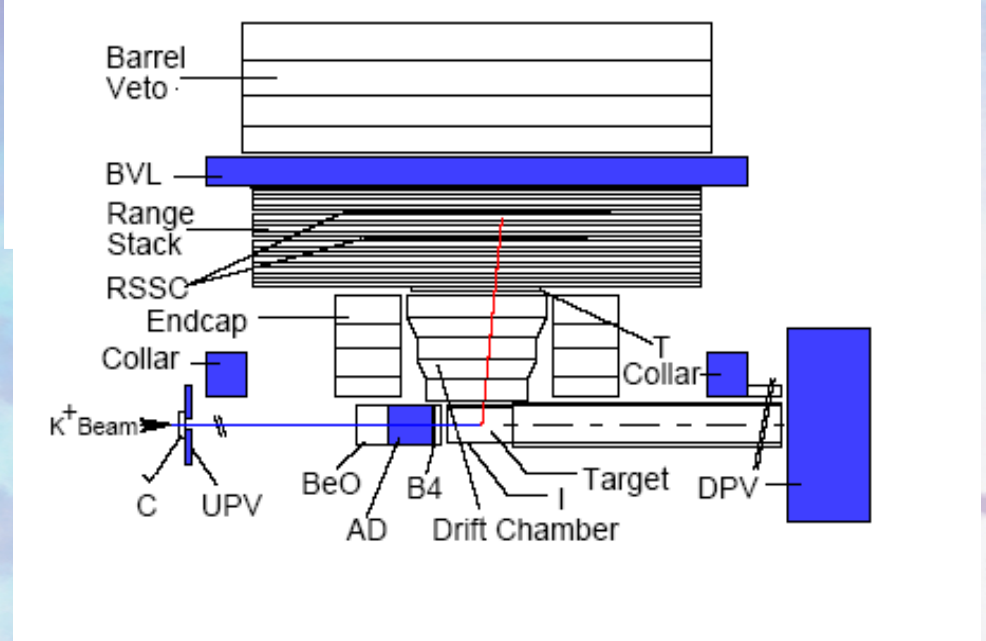
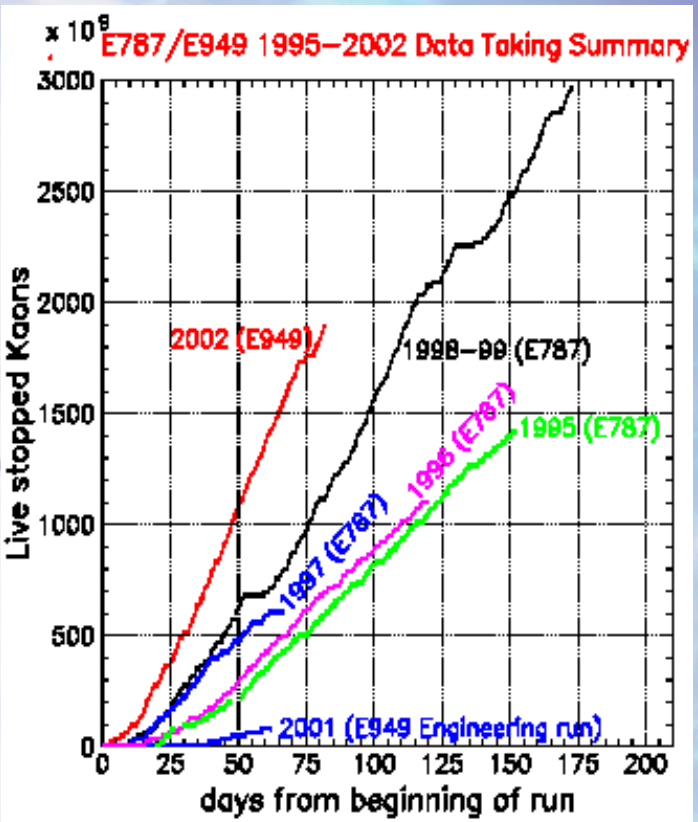
What's new in E949?





- ✓ New/upgraded PV elements
- ✓ More protons from AGS
- ✓ Improved tracking and energy resolution
- ✓ Higher rate capability due to DAQ, electronics and trigger improvements

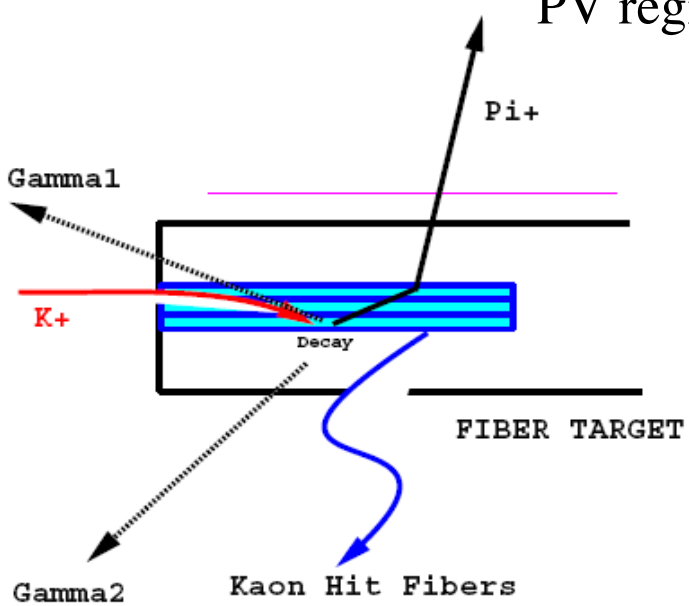
- × *Lower beam duty factor*
- × *Lower proton energy*
- × *Problematic separators, worse K/π ratio*

Peculiarities of the PNN2 region

- ✓ More phase space than PNN1
- ✓ Probes different part of p_π spectrum → enhance validity of PNN1 result
- × More backgrounds, difficult to disentangle from signal and from each other

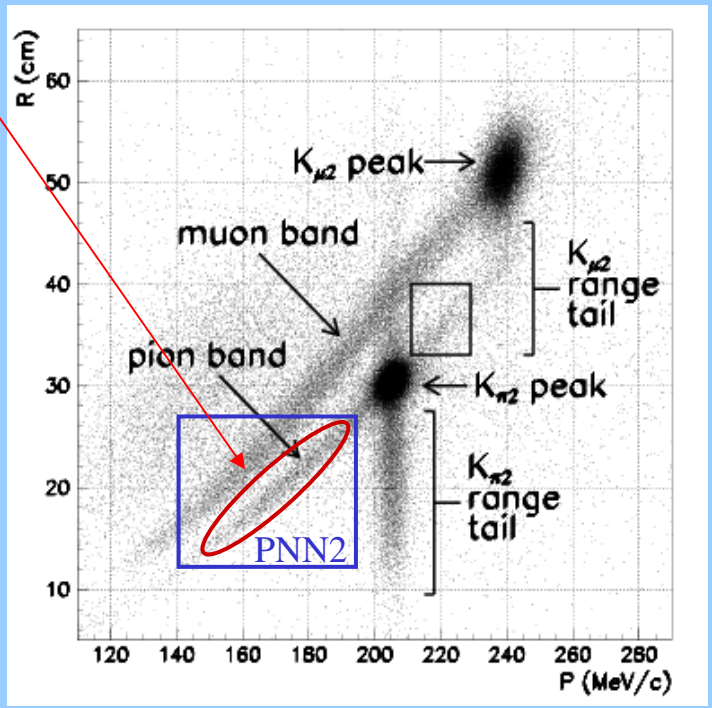
Main background: Kp2 scatters in the Target

- Simultaneous shift in range AND momentum
- Photons head near beam direction, the weakest PV region of the detector



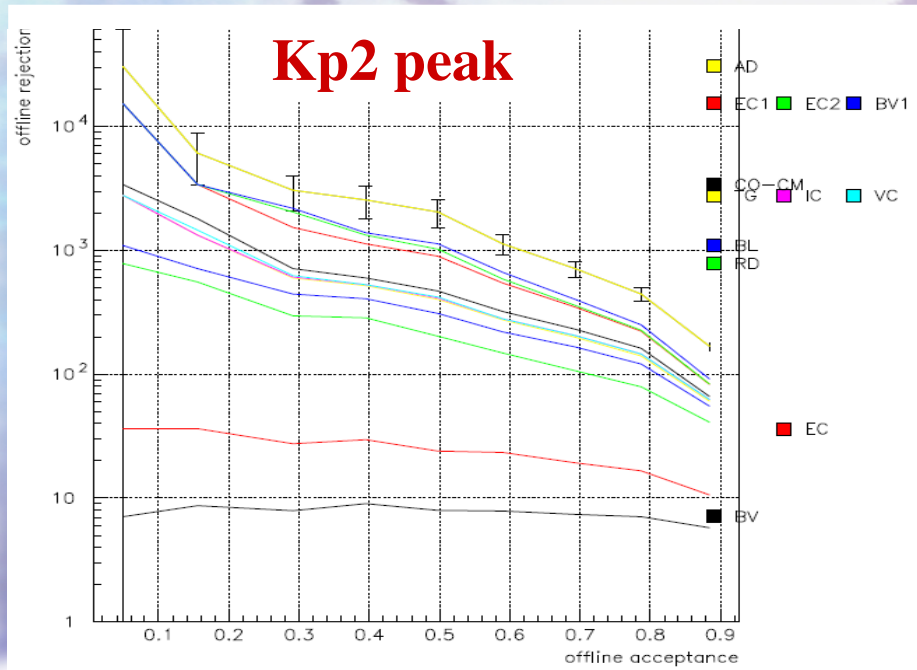
Decay product (π^+ or μ^+) range in scintillator vs momentum:

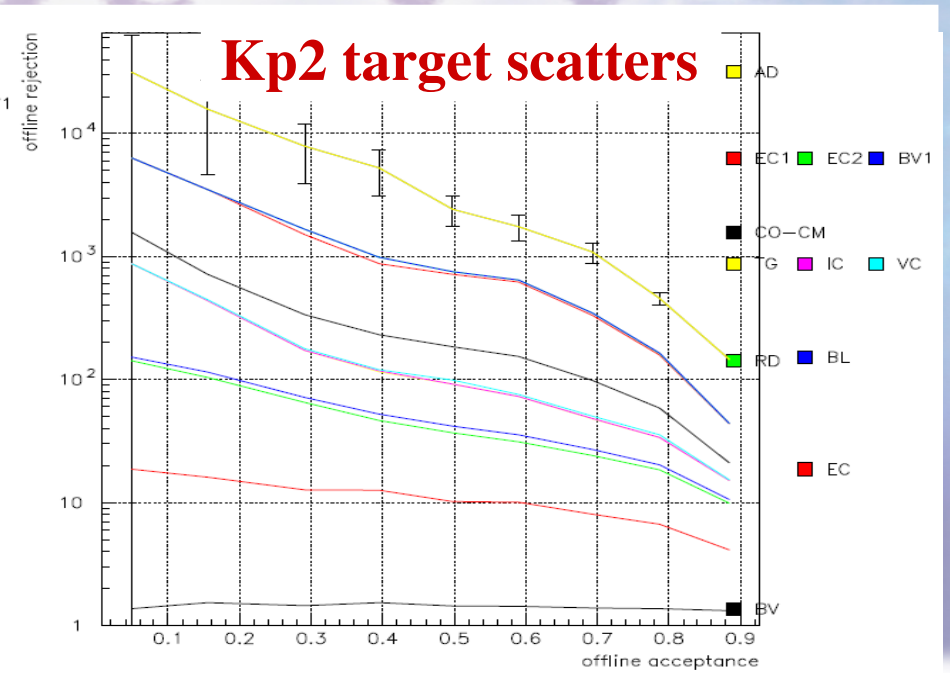
- 2-body decay peaks
- multi-body decay and π^+ scatter bands
- scattering tails



Tools to suppress main background

- **Improved Photon Veto, especially near the beam**
  - **Optimize at the Kp2 peak, check performance with xy-scatters**
  - **Measure rejection on different samples of scatters tagged by different "target quality" criteria ⇒ get a central value and the systematic error**
- Improved algorithms to identify π^+ scatters in target:
  - Transverse (xy-scatters) – pattern finding, fit quality
  - Longitudinal (z-scatters) – double pulse in the fiber due to the scatter, disagreement between TG and UTC information





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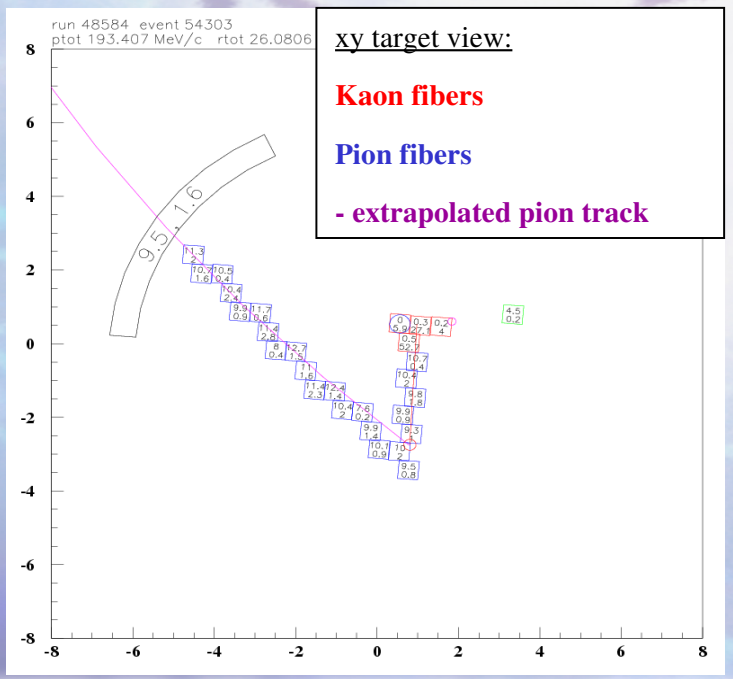

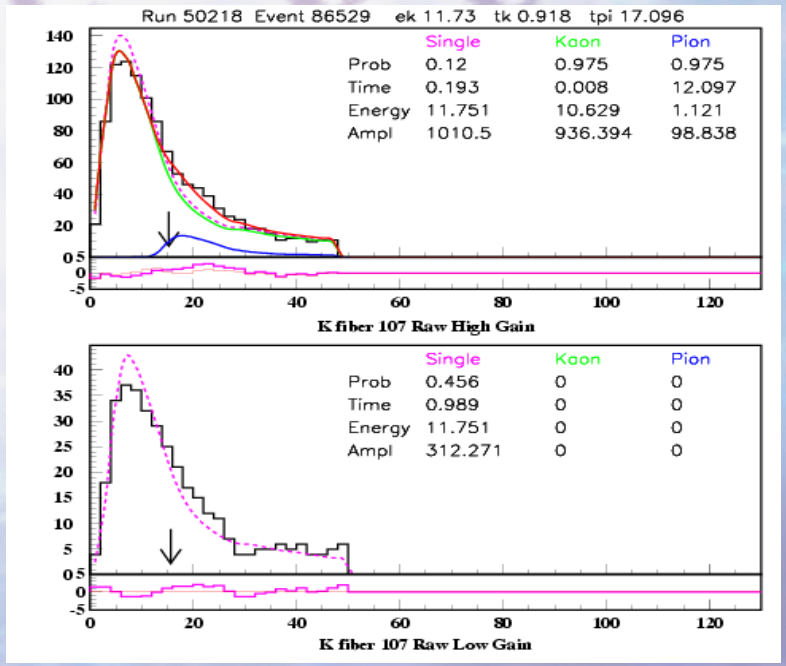

Analysis strategy

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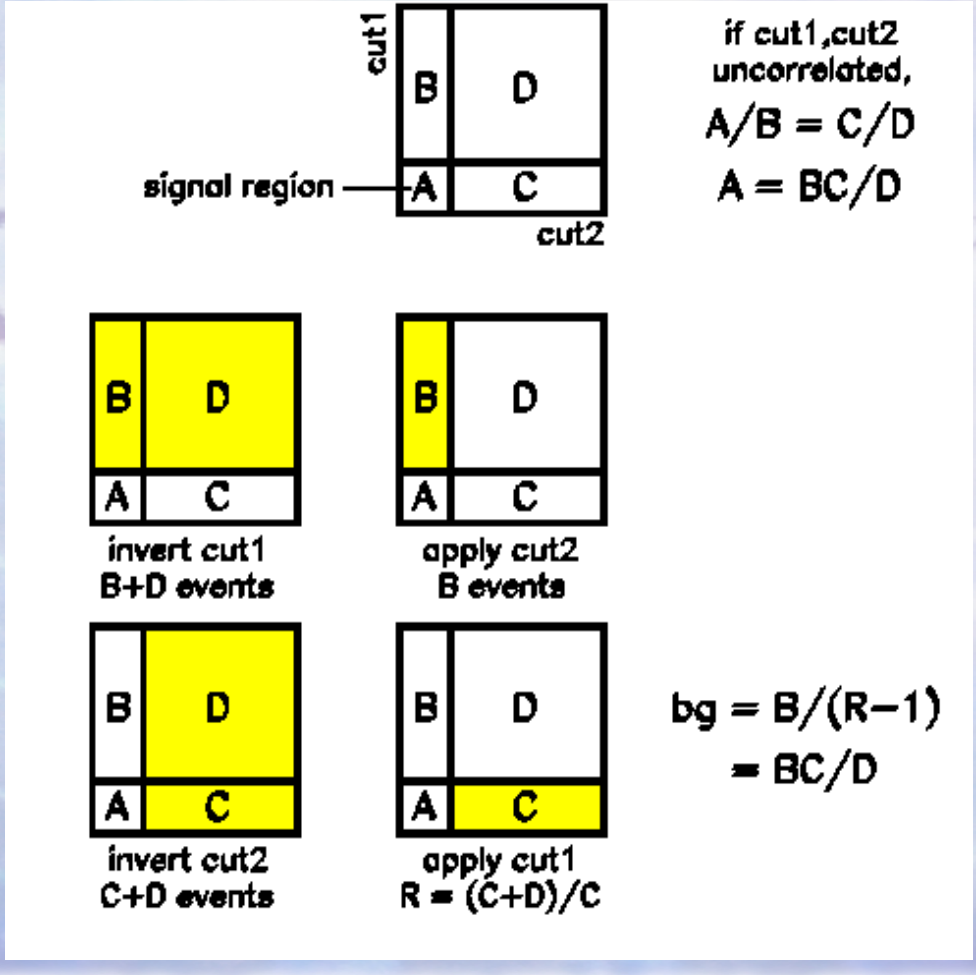
- "Blind" analysis: don't examine signal region until all backgrounds are verified
- To avoid bias, tune cuts using *randomly selected* 1/3 of the data, then measure background with remaining 2/3
- A priori identification of background sources
- Suppress each background source with at least two independent cuts

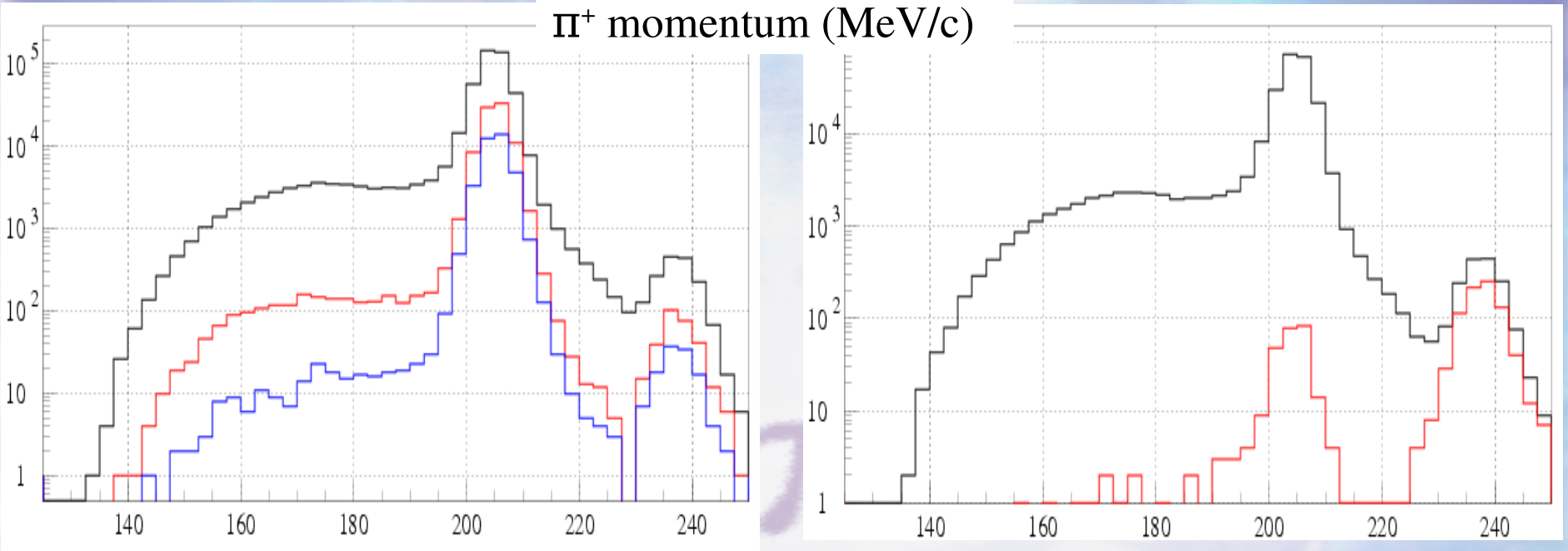
Background	BR ($\times 10^{-3}$)	Suppression method			
		PID	veto	TG	time
$K^+ \to \pi^+\pi^o$ ($K_{\pi 2}$)	209.2	-	$\surd\surd$	$\surd$	-
$K^+ \to \pi^+\pi^o\gamma$ ($K_{\pi 2\gamma}$)	0.275	-	$\surd\surd\surd$	-	-
$K^+ \to \pi^o\mu^+\nu$ ($K_{\mu 3}$)	33.2	$\surd$	$\surd\surd$	-	-
$K^+ \to \mu^+\nu\gamma$ ($K_{\mu 2\gamma}$)	6.2	$\surd$	$\surd$	-	-
$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4})	0.041	-	$\surd$	$\surd$	-
Beam backgrounds:					
single beam	-	$\surd$	-	-	$\surd$
double beam	-	-	$\surd\surd$	-	-
CEX: $K^+n \to K^op$	$R_{K_L} = 2.8 \times 10^{-5}$	-	$\surd$	$\surd$	$(\surd)$
$K_L^o \to \pi^+\mu^-\overline{\nu}$	135.0				
$K_L^o \to \pi^+e^-\overline{\nu}$	194.0				

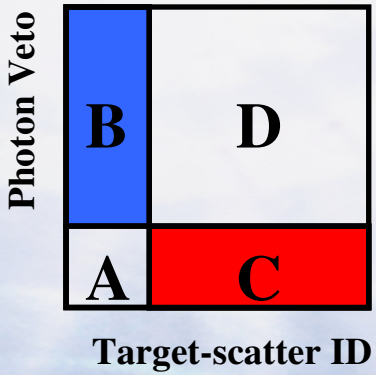
Bifurcated analysis

- Background cannot be reliably simulated ⇒measure with data by inverting cuts and measuring rejection
- For backgrounds that cannot be reliably isolated in data, use MC to measure rejection and data for normalization



$K^+ \rightarrow \pi^+\pi^o$ TG scatters



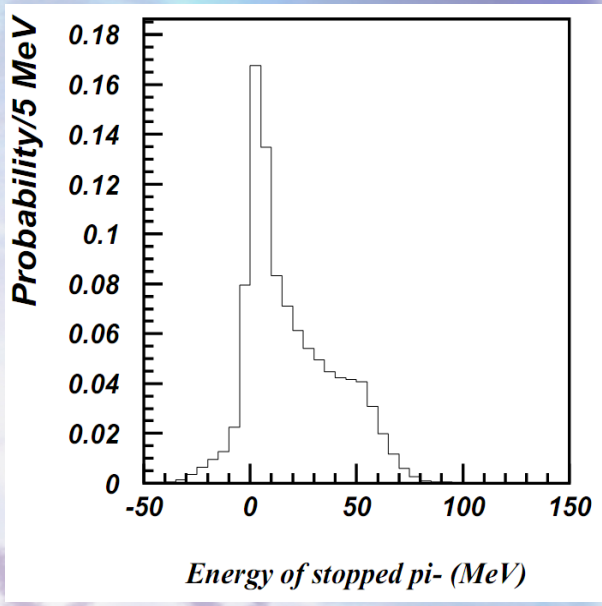


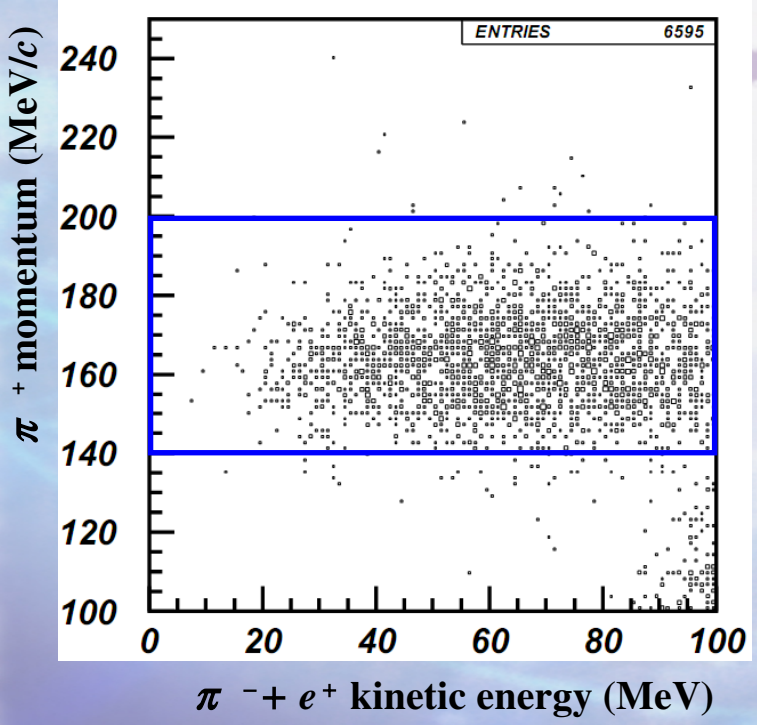
Select events with photons, apply target quality cuts → region B

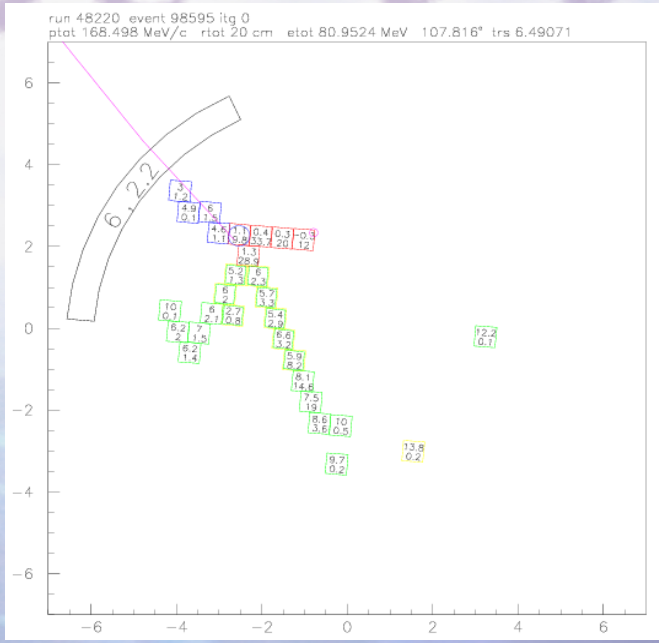
Select events with target scatter, apply PV → measure rejection of photon veto (C+D)/C

$K^+ \rightarrow \pi^+\pi^-e^+\nu$

- Ke4 can be a background if the kinetic energy of the π^- and the e^+ is low, so that they are not detected
- Isolate a pure Ke4 sample from data using target cuts, for normalization
- Find the rejection of those cuts from MC, which uses the measured energy deposit of the π^-

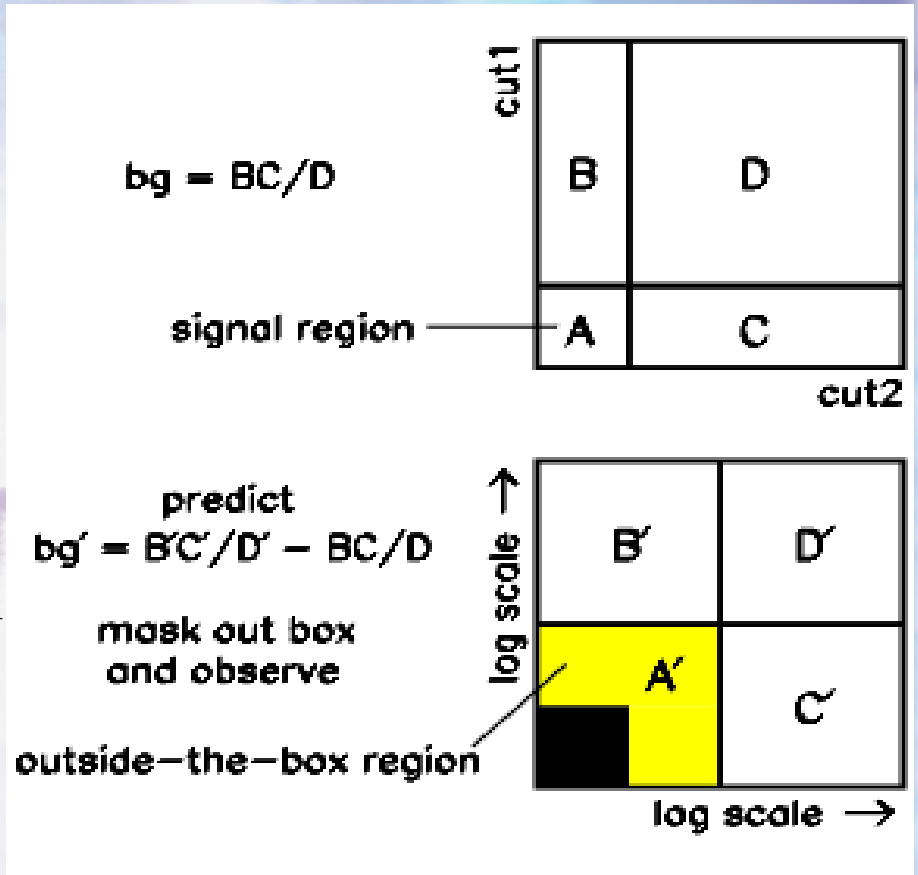






Cross-checks

- Verify background estimates and check for correlations by loosening cuts and comparing observed and predicted number of events remaining near the signal region (*"Outside-The-Box" study*)
- Examine events that failed only one or two (sets of) cuts, to make sure all background sources have been accounted for (*"Single- and Double-Cut-Failure" study*)



Region	$N_{\text{exp.}}$	$N_{\text{obs.}}$	$\mathcal{P}(N_{\text{obs.}}; N_{\text{exp.}})$	Combined
Target-scatter ID	$0.79^{+0.46}_{-0.51}$	0	0.45 [0.29,0.62]	N/A
Photon Veto 1	$9.09^{+1.53}_{-1.32}$	3	0.02 [0.01,0.05]	0.05 [0.02,0.14]
Photon Veto 2	$32.4^{+12.3}_{-8.1}$	34	0.61 [0.05,0.98]	0.14 [0.01,0.40]

Expected background

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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

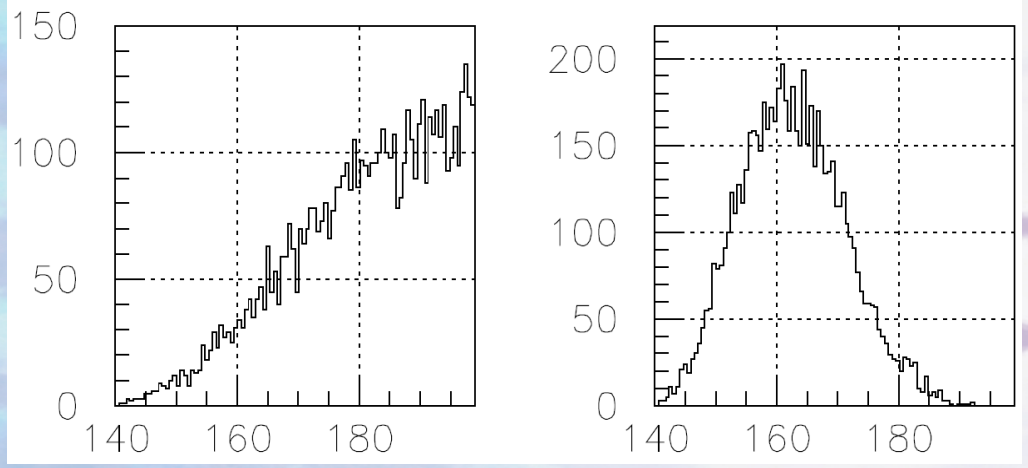
	E949 pnn2	E787 pnn2
Total Kaons	1.70×10^{12}	1.73×10^{12}
Total Acceptance	1.37×10^{-3}	0.84×10^{-3}
SES	4.3×10^{-10}	6.9×10^{-10}

Compared to the E787-PNN2 analysis, the total background decreased by 24% and total acceptance increased by 63%

Division of signal region

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

π^+ momentum (MeV/c) for signal and Ke4 background



- Divide signal region into 9 cells, by varying the PV, kinematic, muon ID and delayed coincidence cuts

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
1	0.93	

Likelihood ratio method

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Calculate the BR using s_i/b_i of cells where event(s) are found, using the likelihood ratio method:

Maximize

$$X = \prod_{i=1}^{n} X_i \quad , \quad X_i = \frac{\dfrac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!}}{\dfrac{e^{-b_i} b_i^{d_i}}{d_i!}}$$

where d_i the number of candidates in cell i, n the total number of cells

Opening the box

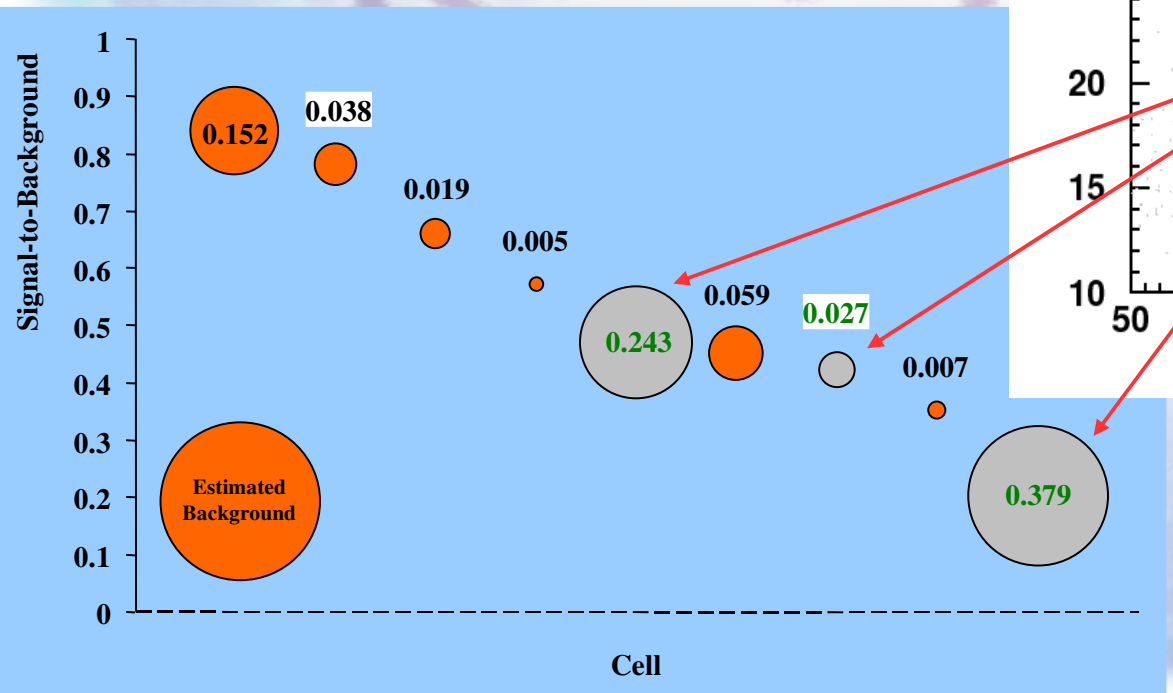
3 candidate events found !

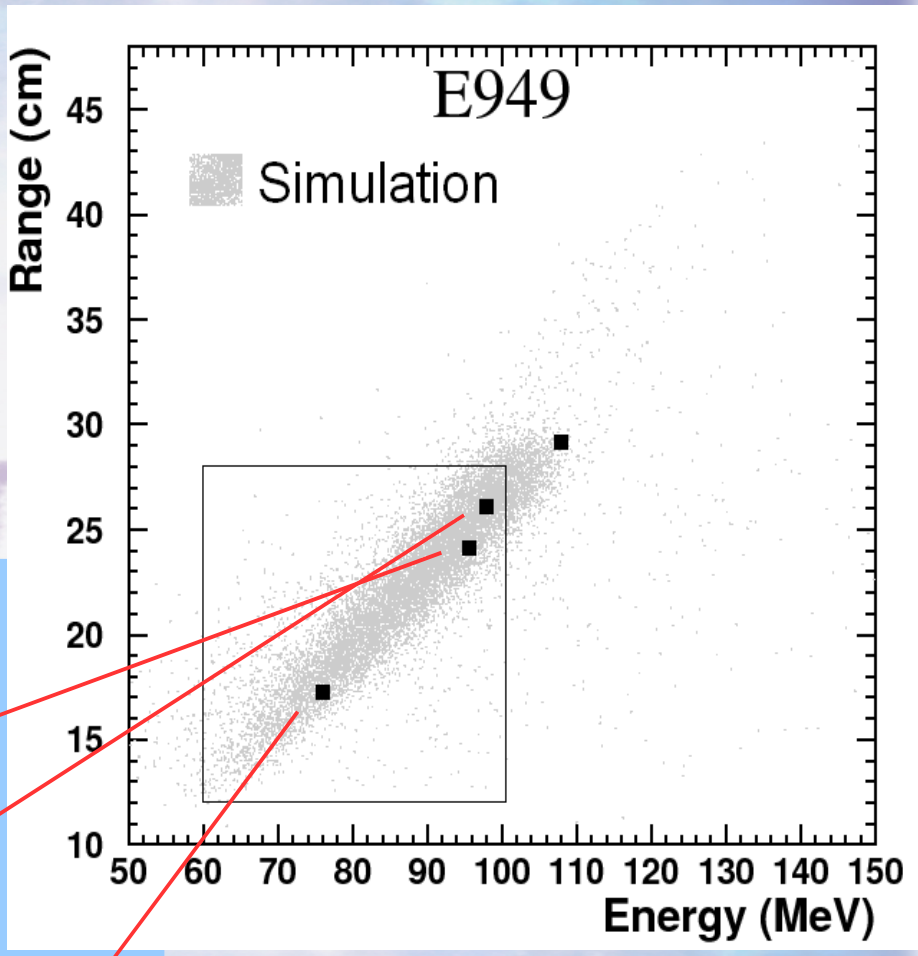
$BR=(7.89^{+9.26}_{-5.10})x10^{-10}$

Probability that all 3 are due to

background: *0.037*

SM signal+background: *0.056*

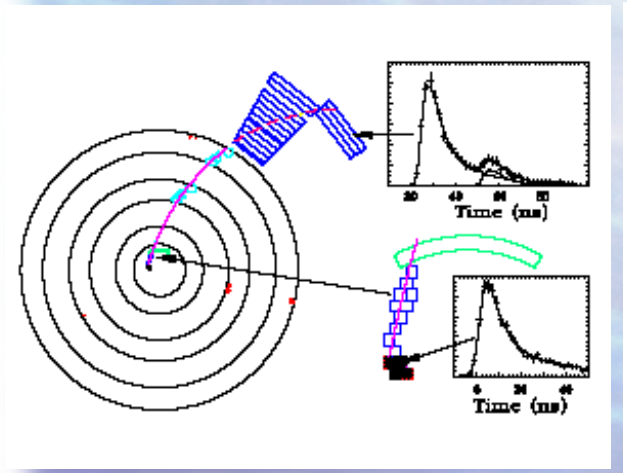




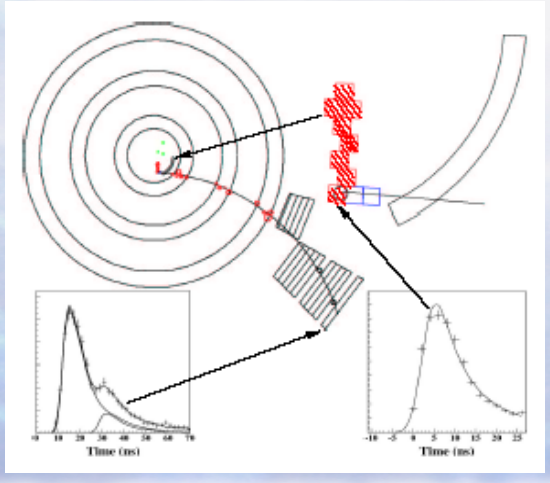
Previous results

	E787		E949	
	PNN1	PNN2	PNN1	PNN2
p(π) MeV/c	[211,229]	[140,195]		[140,199]
Stopped K^+	5.9×10^{12}	1.7×10^{12}	1.8×10^{12}	1.7×10^{12}
Background	0.14±0.05	1.22±0.24	0.30±0.03	0.93±0.17
Acceptance	0.0020	0.0008	0.0022	0.0014
S.E.S.	0.8×10^{-10}	6.9×10^{-10}	2.6×10^{-10}	4.3×10^{-10}
Candidates	2	1	1	3
BR ($\times10^{-10}$)	$1.57^{+1.75}_{-0.82}$	<22 (90% CL)	$1.47^{+1.30}_{-0.89}$	$1.73^{+1.15}_{-1.05}$

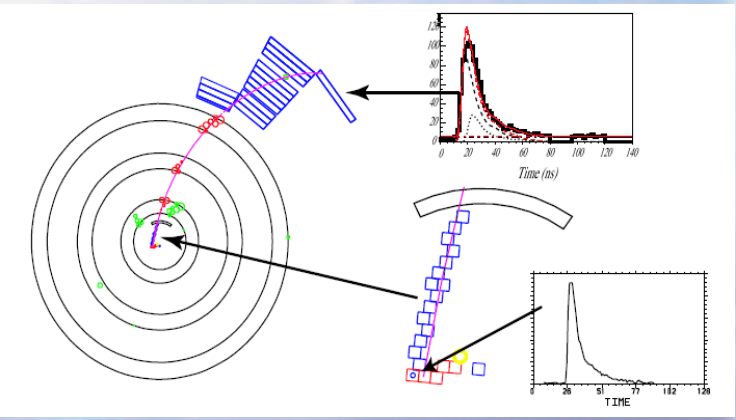
Candidate E787A



Candidate E787C



Candidate E949A



Combined result

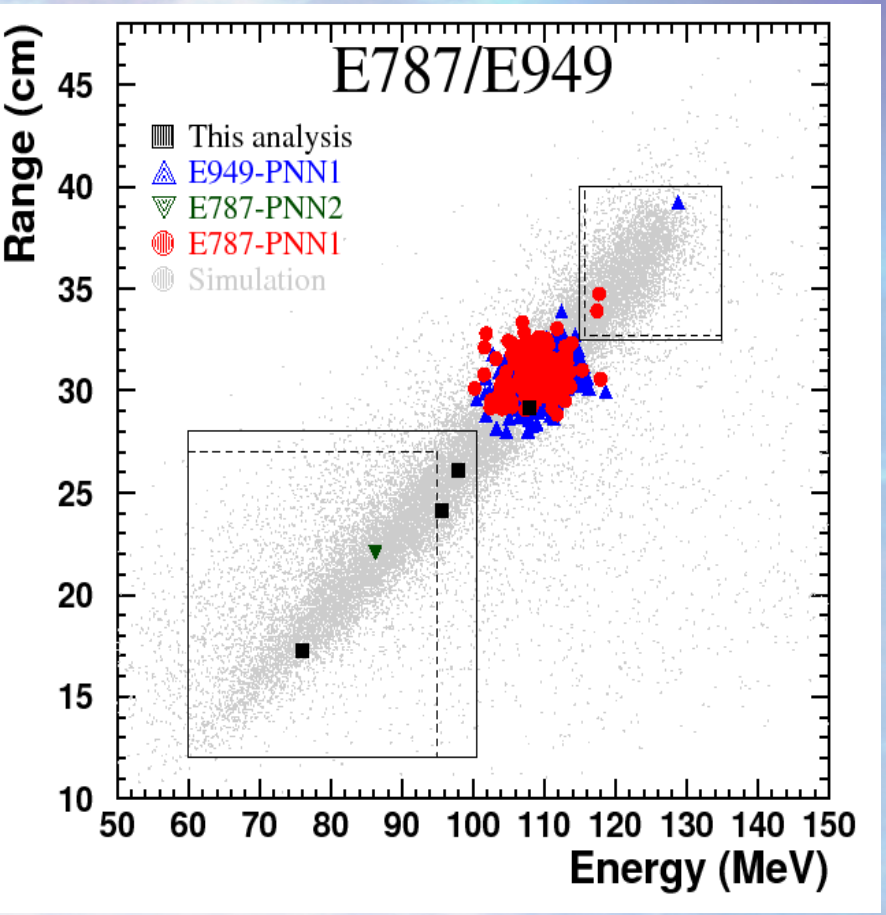
7 candidate events in total

$BR=(1.73^{+1.15}_{-1.05})x10^{-10}$

Probability that all 7 are due to

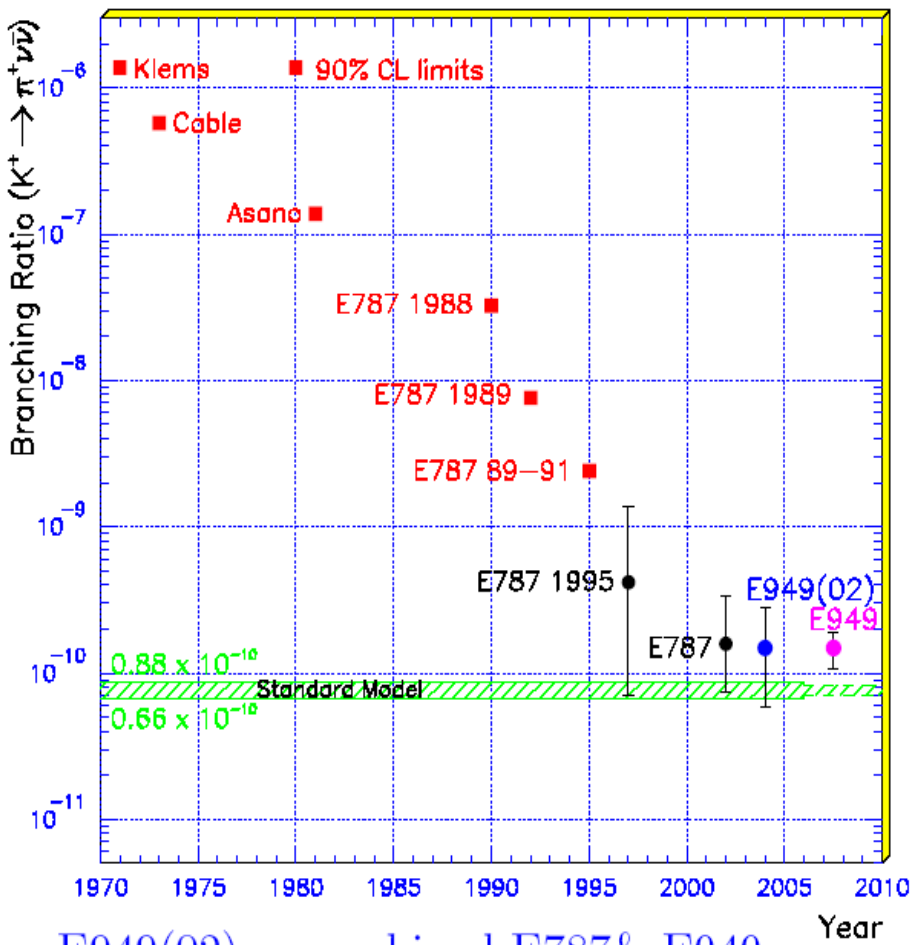
background: *0.001*

SM signal+background: *0.060*



Central value, although still ~ 2× SM , it is consistent with it within errors…

Progress and future prospects



E949(02) = combined E787& E949.

E949 projection with full running period.

- Obviously, more statistics are needed →it would have been nice if E949 had all its promised running time...
- Fortunately others have taken over: NA62 at CERN, E391a at JPARC, Project X at Fermilab(?)

Conclusions

- E787 upgrade into E949 worked as expected
- Final bit of the puzzle is now in place (PNN2 measurement), and E787/E949 have a final and definitive result
- Thanks to detector upgrades and deeper understanding of the analysis techniques, the PNN2 study was fruitful and observed 3 candidate events with an expected background of ~1
- The combined BR measured by E787/E949 in both kinematic regions is $\bar{BR}(K^+ \rightarrow \pi^+ \nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$, which is still consistent with the SM
- More experiments are running or are under preparation, set to constrain the CKM parameters from the Kaon sector – ***good luck!***

Extras

CKM matrix

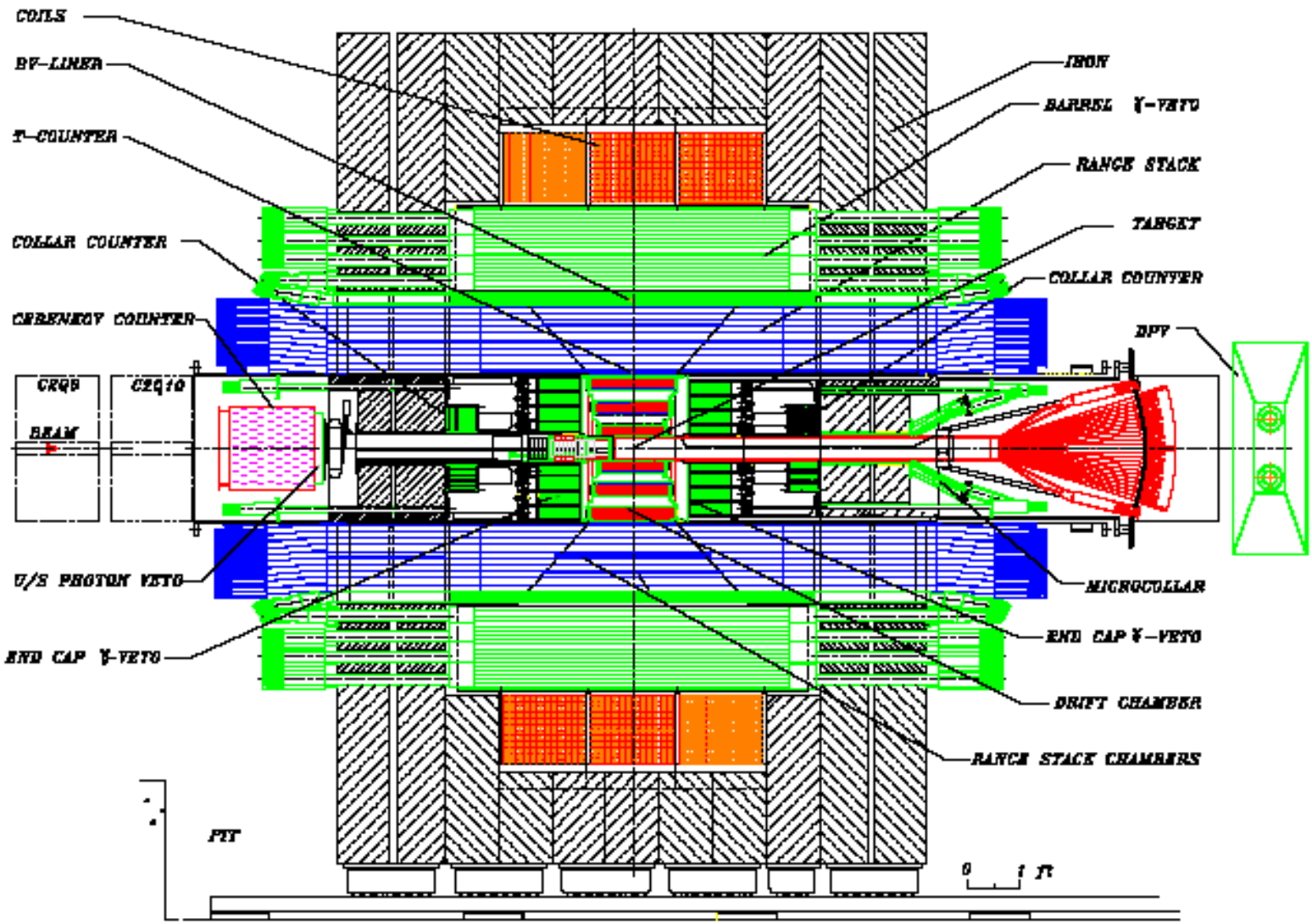
The CKM matrix relates weak with mass eigenstates. In the Wolfenstein parametrization,

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

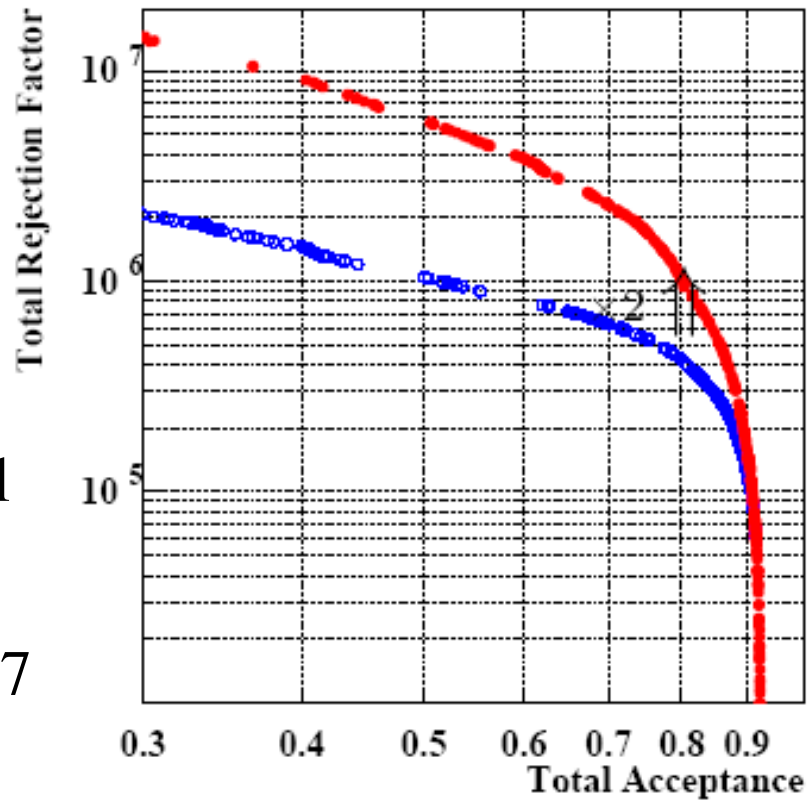
where $\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right)$, $\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$

CP violation arises from the irreducible phase of V_{CKM} , because it's 3x3 (3 generations)

The E949 detector



Photon Veto improvement



~ 2 × better rejection at nominal PNN1 acceptance (80%) or

~ 5% more acceptance with E787 rejection !

* Good news for PNN2 as well…

E787, E949

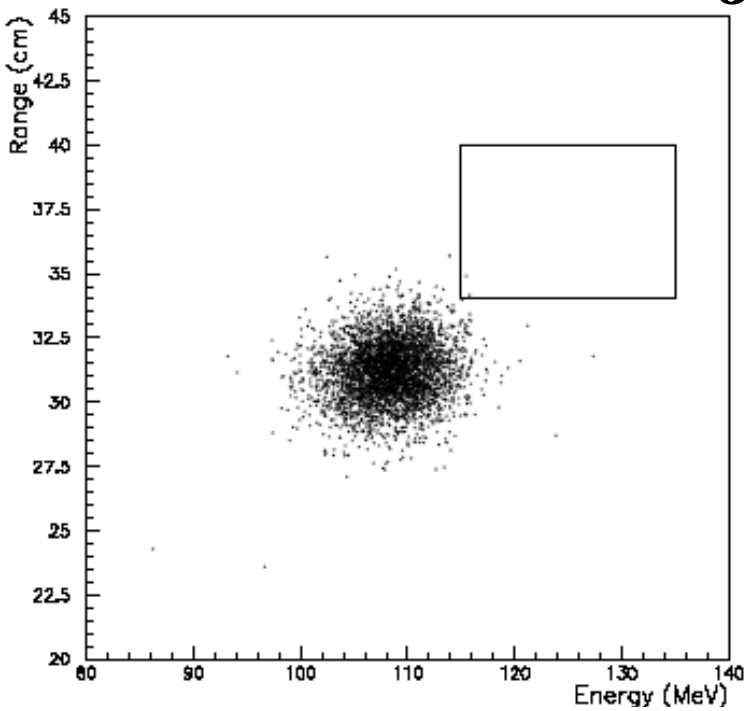
Analysis strategy (1)

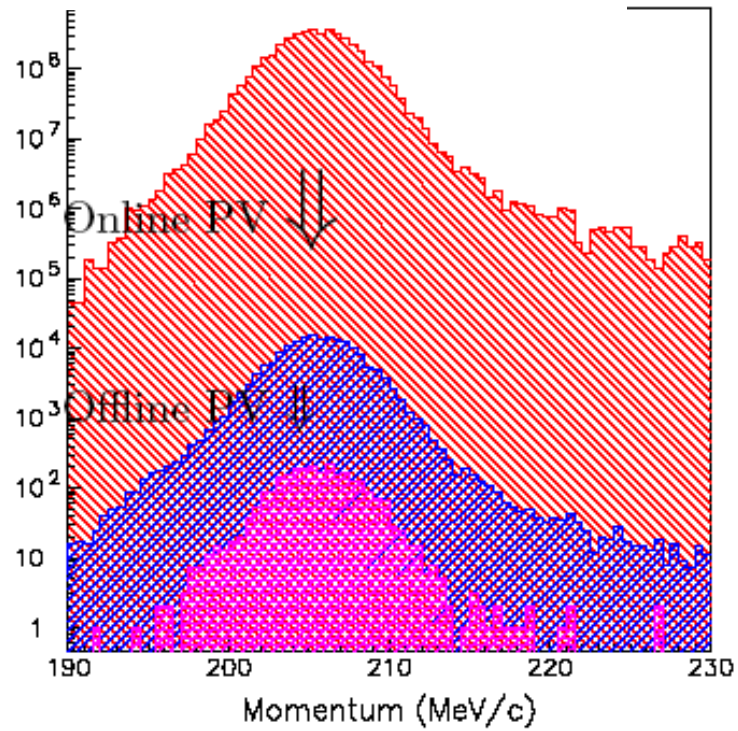
- "Blind" analysis: don't examine signal region until all bg are verified
- To avoid bias, tune cuts using *randomly selected* 1/3 of the data, then measure bg with remaining 2/3
- A priori identification of bg sources
- Suppress each bg source w/ at least two independent cuts
- Bg cannot be reliably simulated ⇒measure w/ data by inverting cuts and measuring rejection

	Suppresion method			
Source	Kinematics	Particle ID	Veto	Timing
$K^+ \to \mu^+\nu(\gamma)$ ($K_{\mu 2}$)	√	√	(√)	
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	√		√	
Scattered π^+ beam		√		√
CEX			√	√

CEX $\equiv K^+ n \to K^0 p$, $K_L^0 \to \pi^+\ell^-\nu$

Example: $K^+ \rightarrow \pi^+\pi^o$ bg rejection





Select events with photons, measure rejection of kinematic cuts (P, R, E "box")

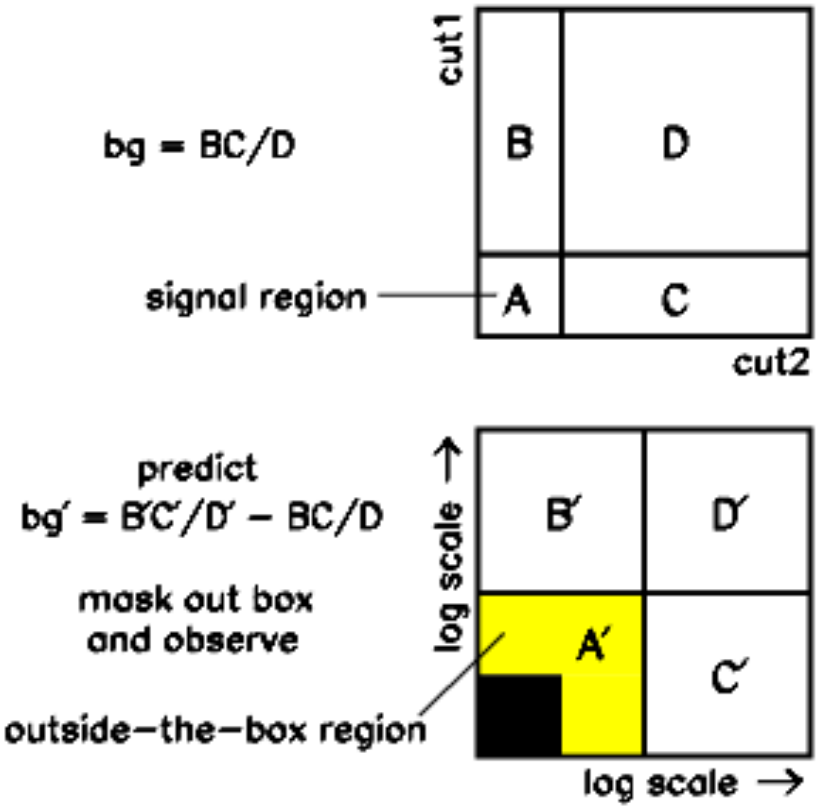
Select $K^+ \rightarrow \pi^+\pi^o$ kinematically, measure rejection of photon veto

Analysis strategy (2)

- Verify bg estimates & check for correlations by loosening cuts and comparing observed and predicted number of events remaining.
- Construct background functions by varying *one cut at a time*, keeping the other inverted. Use them to estimate bg in the signal region.
- Use MC to measure geometrical acceptance, verify by measuring $BR(K^+ \rightarrow \pi^+ \pi^o)$

Analysis strategy (3)

- Verify bg estimates & check for correlations by *simultaneously* loosening both cuts and comparing observed and predicted number of events remaining. Construct background functions by varying *one cut at a time*, keeping the other inverted.

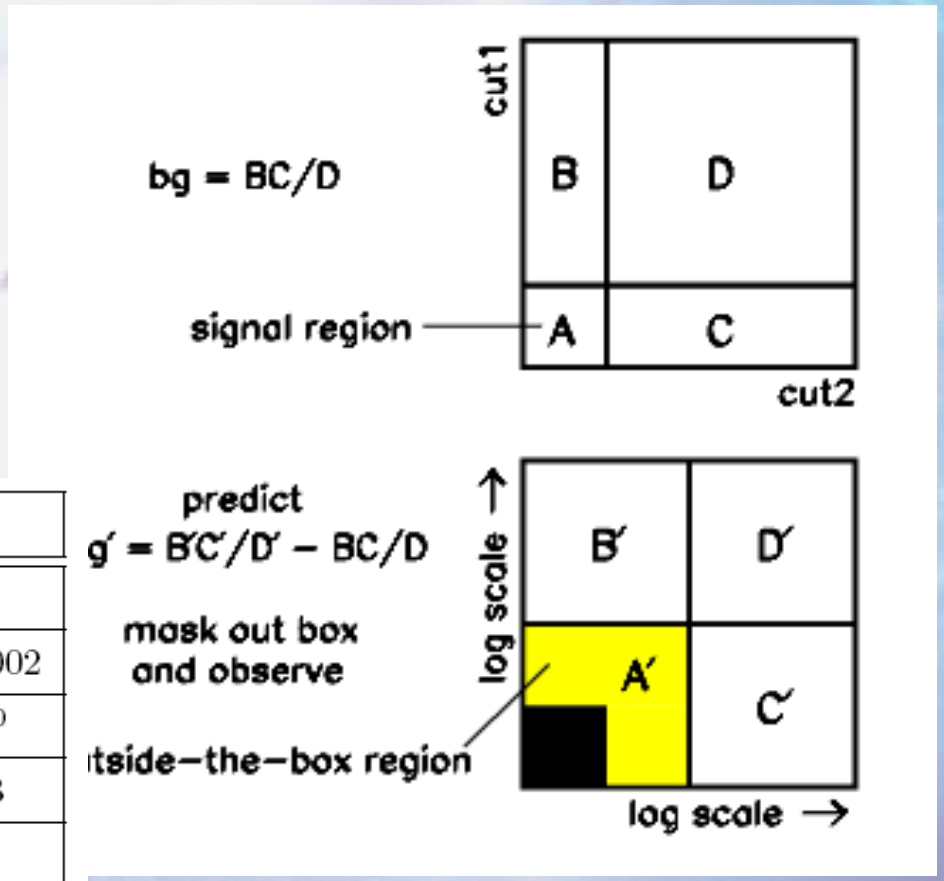


OTB study & acceptance measurement

- Verify bg estimates & check for correlations by loosening cuts and comparing observed and predicted number of events remaining ("outside-the-box" study).

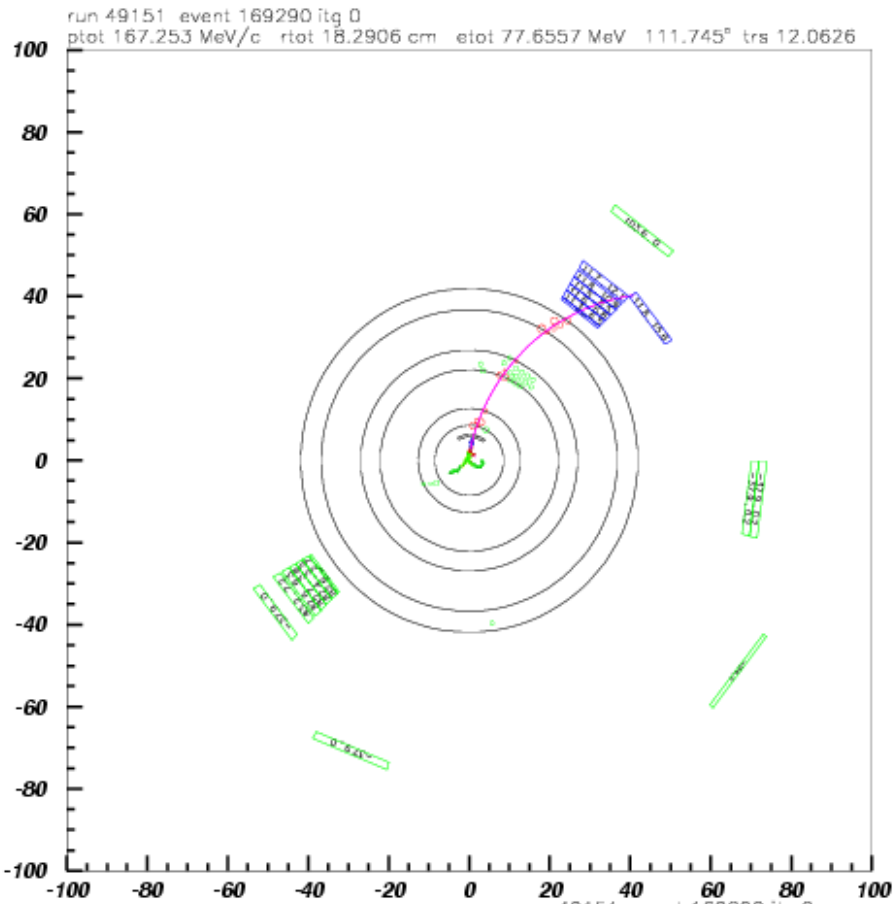
Acceptance measurement:

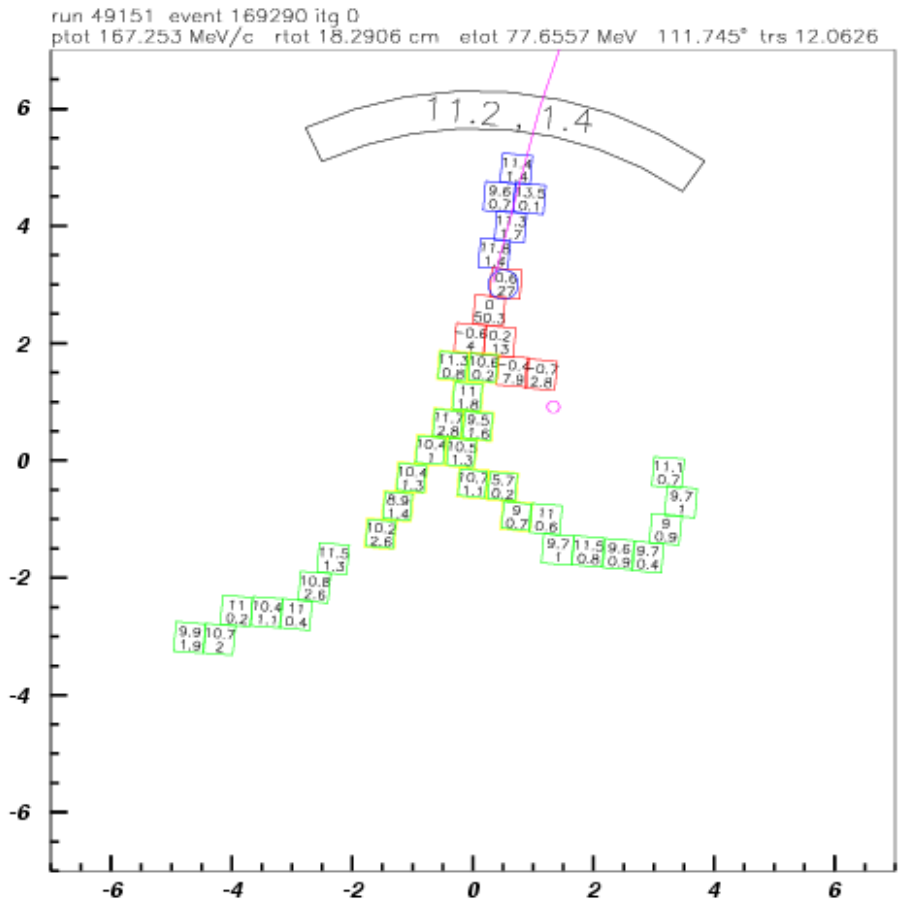
- Use special background samples (with loose trigger) to measure cuts' and part of trigger acceptance
- Use signal MC to measure geometrical acceptance



	E787		E949
Stopped K^+ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

$K^+ \rightarrow \pi^+\pi^-e^+\nu$





$K^+ \rightarrow \pi^+\pi^o$ TG scatter event