First results from BNL E949 on the rare decay $K^+ \rightarrow \pi^+ \nu\nu$

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for BNL E949 collaboration

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Alberta/British Columbia/TRIUMF (Canada)

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Outline

- Introduction
- The E949 experiment
- Analysis
- Results
- Conclusions

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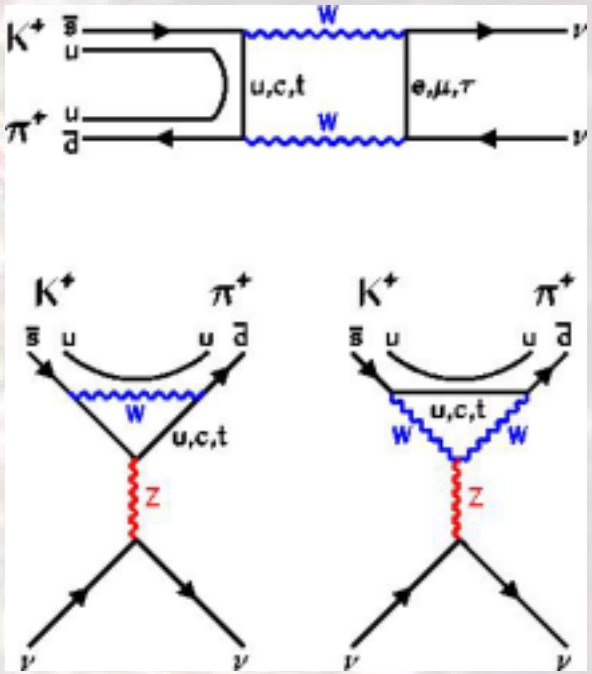
Introduction

- $K^+ \rightarrow \pi^+ \nu\nu$ in the Standard Model
  - Z penguin and Box diagram
  - Top in the loop, Sensitive to $|V_{td}|$
    - Charm contrib. well calculated
  - Small theoretical uncertainty ~7%
  - ➢ One of golden modes to explore CKM matrix
  - Br (SM) ≈ 0.8×10^{-10}

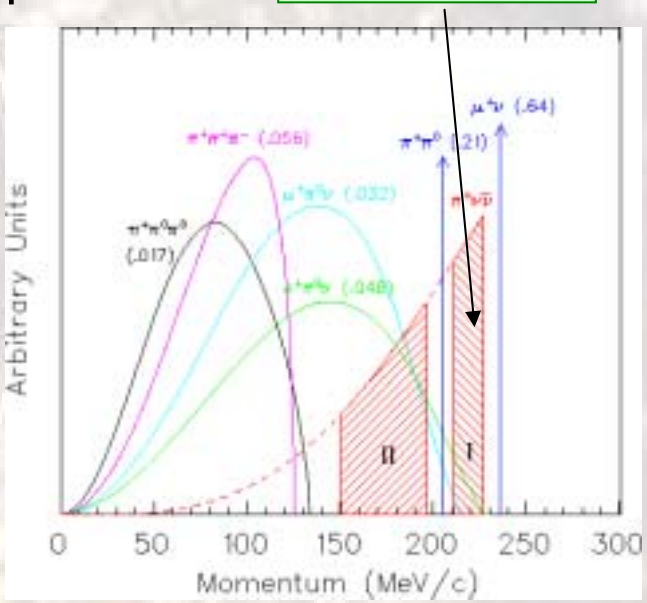


- Experimental status
  - 2 events observed by BNL E787 (1995-98)
    - ➢ BR=1.57(+1.75/-0.82) x 10^{-10}
  - Now, E949, as the successor of E787, aimed at 5-10 SM events

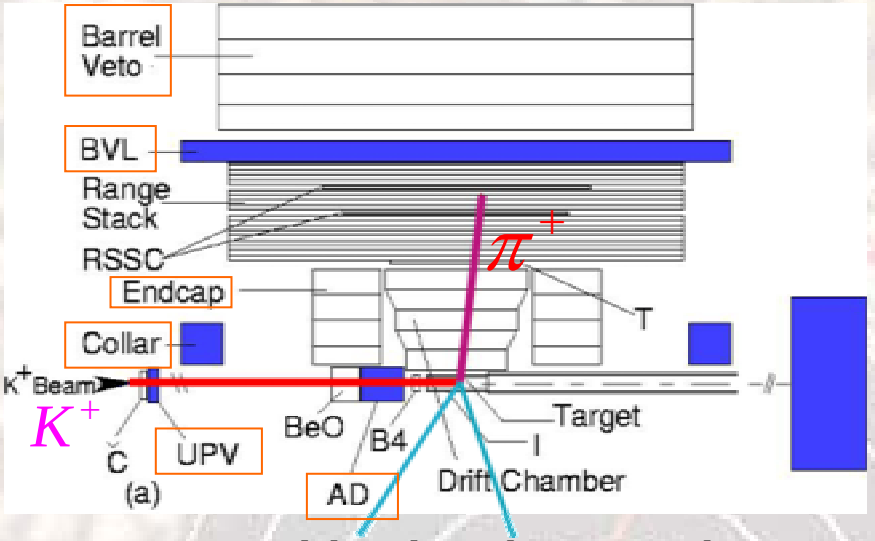
E949 Experiment

- Event signature = K^+ comes in, only π^+ comes out
- Basic concepts (common to E787)
  - Stopped K^+ experiment
  - Measure full kinematics of decay particle (π^+)
    Energy (E) / Momentum (P) / Range (R)
  - PID by recording π-μ-e decay chain
  - Hermetic veto detectors (γ)
  - ➢ Reduce two major backgrounds
    - $K^+ \rightarrow \mu^+\nu$ (Br=63%)
      - Kinematics (monochromatic)
      - PID (π/μ separation)
    - $K^+ \rightarrow \pi^+\pi^0$ (Br=21%)
      - Kinematics (monochromatic)
      - Photon veto

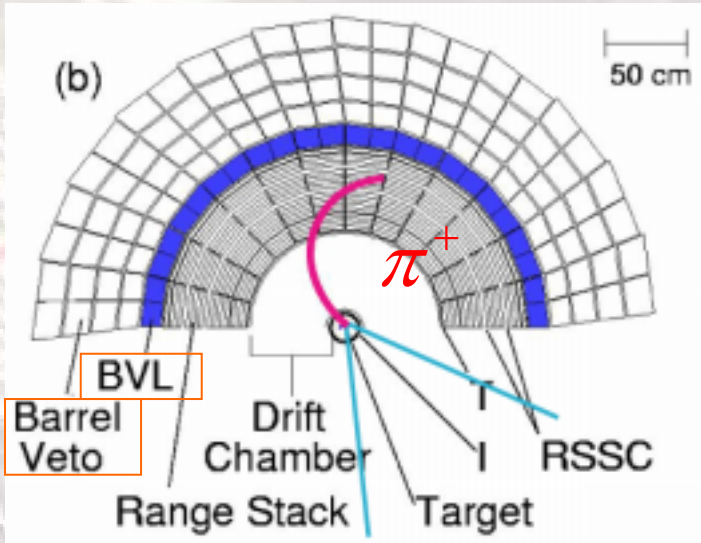
Signal region in this analysis



E949 Detector



Side view (cutaway)



End view (top half)

- Active target (scintillation fibers) to stop K^+
- Drift chamber and the magnetic field to measure π^+ momentum
- 19 layers of scintillators ("Range Stack") to measure E and R
- Waveform digitizer to record π-μ-e decay chain in the π^+ stopping RS counter

Renew inner 5 layers!
Equip gain monitor!

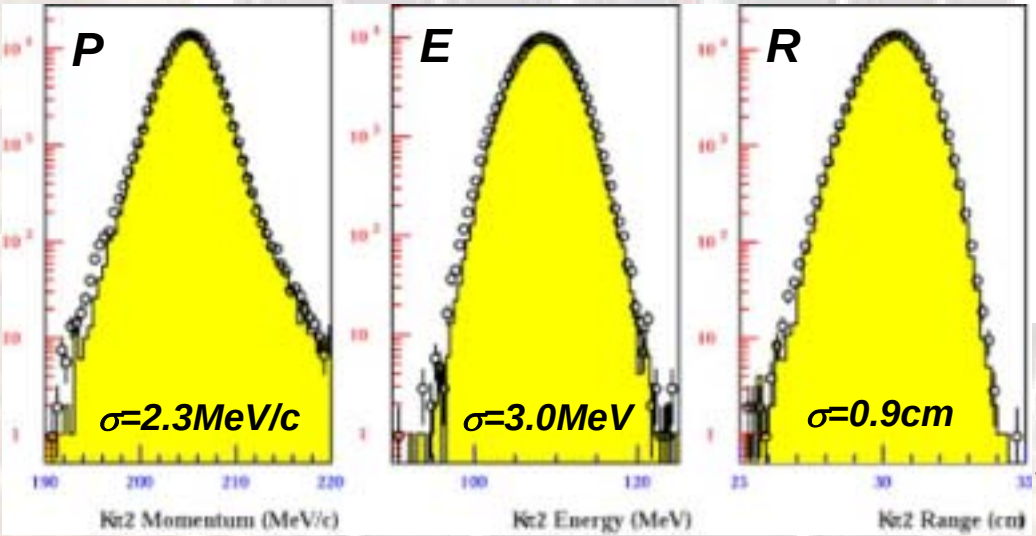
New!

- Photon vetoes surrounding 4π solid angle (BV / BVL / Endcap /…)

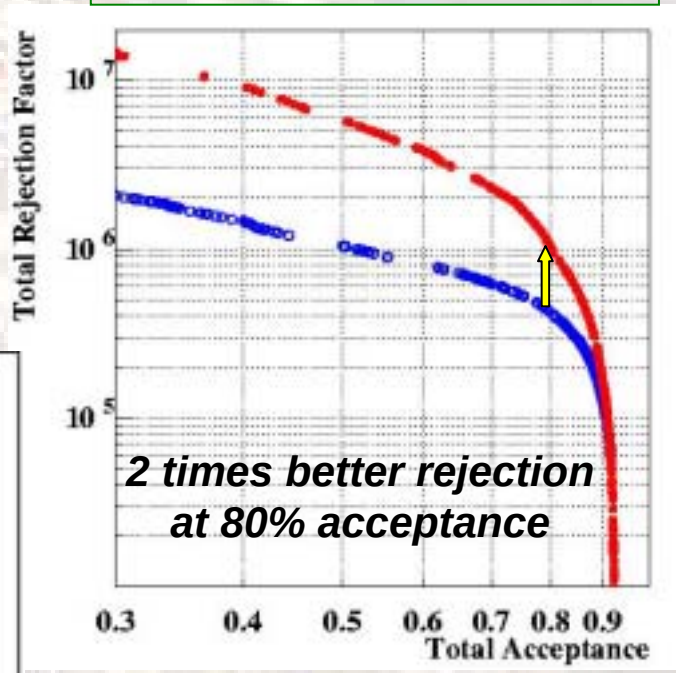
Highlight of Upgrade - from E787 to E949 -

- To having higher sensitivity…
  - 2 times higher beam intensity
  - Better photon vetoes
  - Better kinematics measurement

Kπ2 momentum, energy and range
E949 (yellow histogram) vs. E787 (circle)



Kπ2 Rejection
E949 (red) vs. E787 (blue)

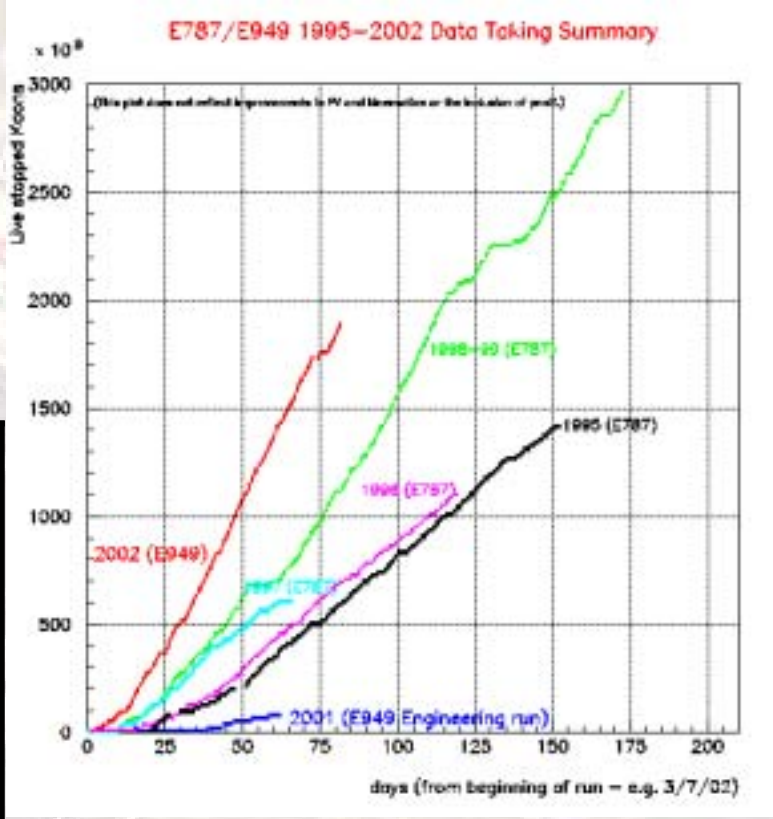


Same or even better resolution in 2 x higher rate environment

Physics Run in 2002

- 12 weeks in 2002
  (1/5 of approved 60 weeks)
  - Detector worked well
  - Data taken smoothly
- Accumulated $K^+=1.8\times10^{12}$

		E787	**E949**
AGS energy	GeV	24	**22**
Beam intensity	Tp	25 – 40	**70**
Duty factor	%	52	**41**
K/π ratio		4	**3**
Accumulated K^+	10^{12}	5.9	**1.8**

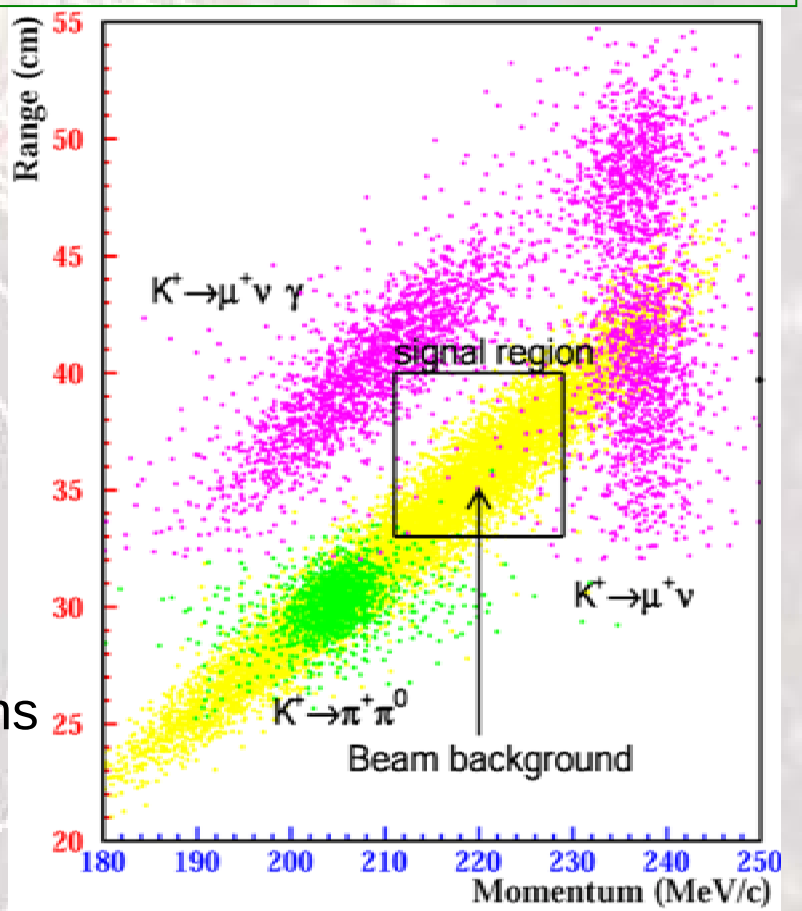


Conditions not optimized due to … AGS power supply failure (energy, duty factor)
DC separator trouble (K/π ratio)

Analysis Overview

- Signal
  - P > P(Kπ2) region ("PNN1")
- Background sources
  - $K^+ \rightarrow \pi^+\pi^0$
  - $K^+ \rightarrow \mu^+\nu$, $\mu^+\nu\gamma$
  - Beam backgrounds
- Strategy
  - Blind analysis
  - Evaluate background level with real data
    - characterized by functions
  - Likelihood ratio technique

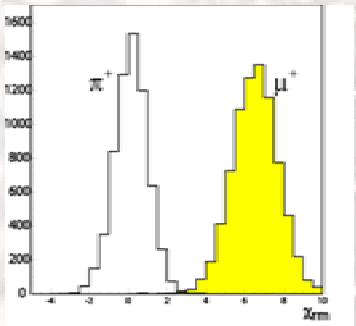
How do signal/backgrounds look like in the R-P plane?



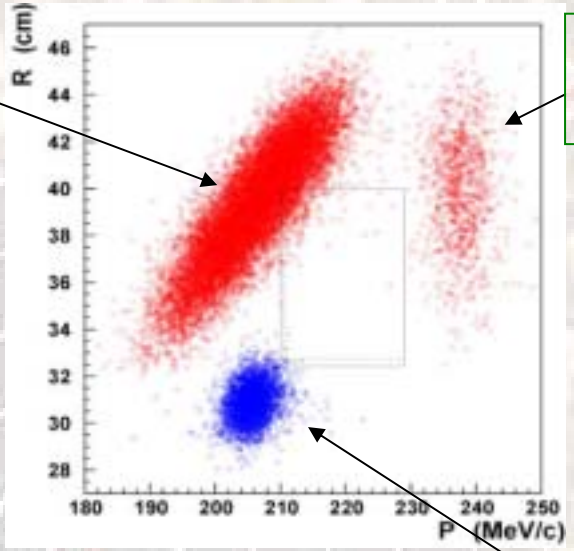
Evaluation of Backgrounds

- Invert one of the cuts and then measure BG rejection

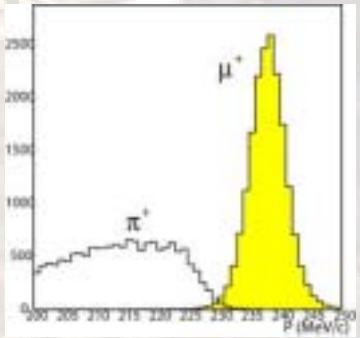
$K^+ \rightarrow \mu^+ \nu \gamma$, …
χ_{rm} and NN function



$\chi_{rm} = (R_{meas} - R_{expect})/\sigma_R$

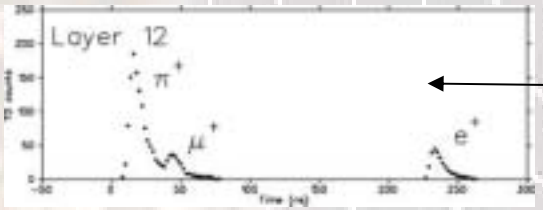


$K^+ \rightarrow \mu^+ \nu$, but short range
P and NN function

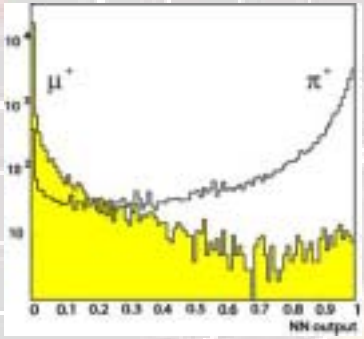


P for π and μ

$K^+ \rightarrow \pi^+ \pi^0$
P(E,R) and Photon veto



π-μ-e decay chain in the π stopping RS



Neural net function for π and μ

BG level evaluated as functions of cut positions

Sensitivity and Background

- Sensitivity

	E787	E949	
N_K (10^{12})	5.9	1.8	**x 0.305**
Acceptance (%)	0.20 ± 0.02	0.22 ± 0.02	**x 1.1**
Sensitivity (10^{-10})	0.83	2.6	**x 0.336**

- Background
  - 10% larger acceptance, by enlarging the signal box to lower edge of E/P/R space, resulting in larger $K\pi2$ backgrounds

Source	E787	E949
$K\pi2$	0.032	0.216 ± 0.023
$K\mu2$	0.064	0.044 ± 0.005
$K\mu\nu\gamma$, …		0.024 ± 0.010
Beam	0.050	0.014 ± 0.003
Total	**0.14 ± 0.05**	**0.298 ± 0.026**

- All the cuts fixed and BG level estimated.

  Now, how to calculate the branching ratio?

Likelihood method

- The signal region is divided into cells by binning parameter space (E,P,R,NN func, photon veto…)
  - Once cuts are fixed, calculate BG level in each cell $\mathbf{b_i}$
  - Expected signal $\mathbf{S_i}$ from **BR** and calculated acceptance $\mathbf{A_i}$

    $\mathbf{S_i}$ = **BR** (as a free parameter) x $\mathbf{N_K}$ x $\mathbf{A_i}$
- Likelihood technique in small S_i, b_i (T.Junk, NIM **A434**, 435 (99))
  - Ratio of two Poisson probabilities (S+B or B only)
  - Estimator defined as

$$X(BR) = \prod_{i=1}^{n} \frac{\exp^{-(S_i+b_i)}(S_i+b_i)^{d_i}}{d_i!} \Bigg/ \frac{\exp^{-(b_i)}(b_i)^{d_i}}{d_i!} = \prod_{i=1}^{n} \exp^{-S_i}\left(1+\frac{S_i}{b_i}\right)^{d_i}$$

($\mathbf{d_i}$ = # of observed candidate in the cell)

➢ When **maximum X(BR)**, the central value of the **BR**

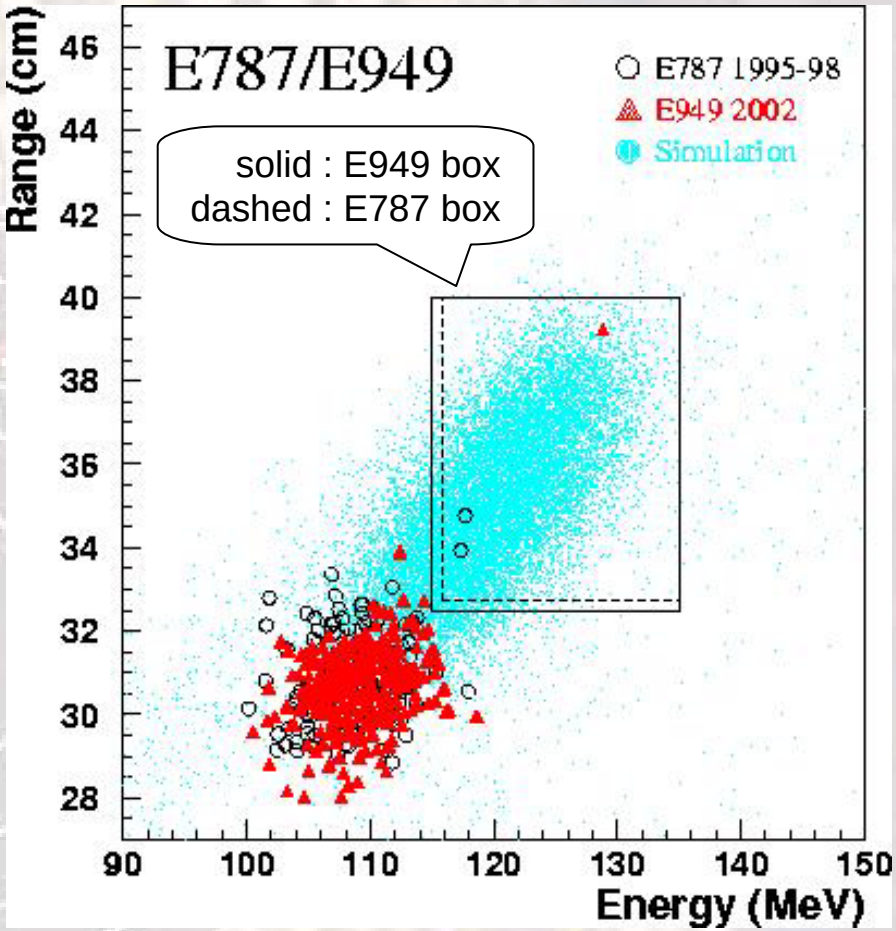
Open the Box

- Range vs Energy after all the cuts
- ➢ Single candidate in the box !!

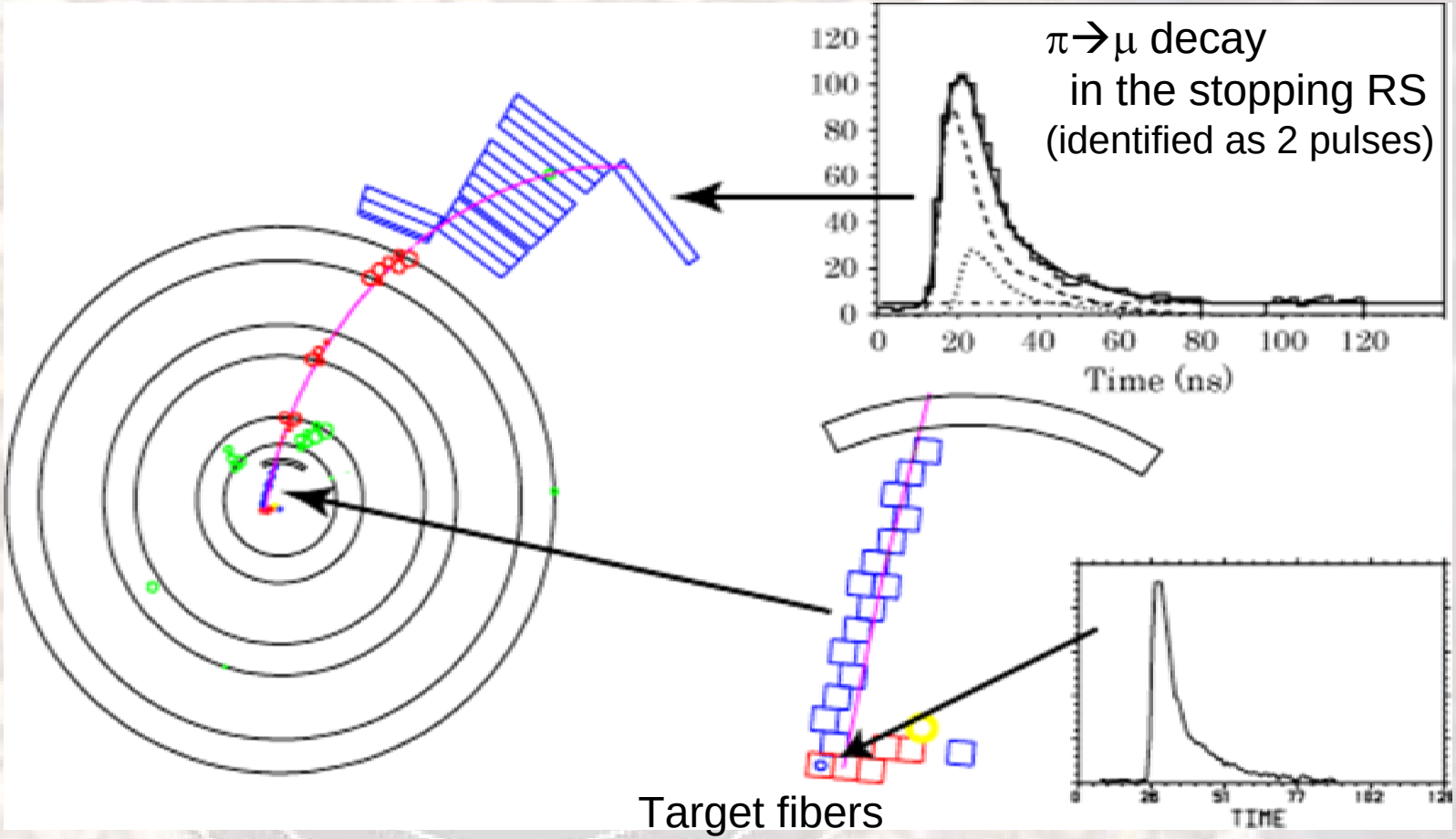
▲ **E949** ○ E787

● Simulation

Details	
Momentum (MeV/c)	227.3
Range (cm)	39.2
Energy (MeV)	128.9
$K^+ \rightarrow \pi^+$ decay time (ns)	4.3
$\pi^+ \rightarrow \mu^+$ decay time (ns)	6.2
$\mu^+ \rightarrow e^+$ decay time (ns)	1370



Event Display



Target fibers
around K^+ stopping

Branching Ratio

- E949 alone

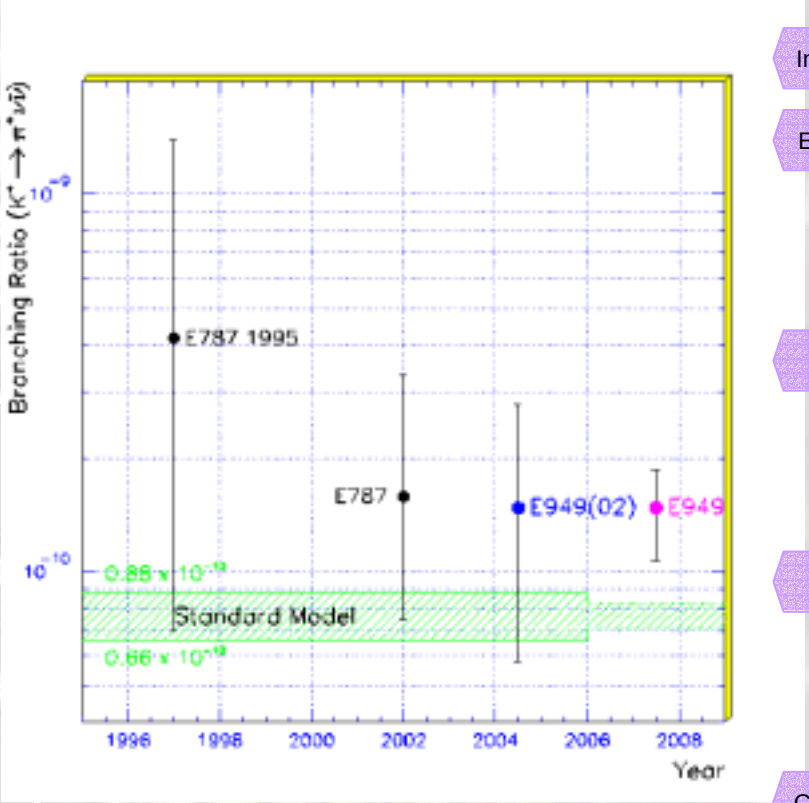
$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = 0.96^{+4.09}_{-0.47} \times 10^{-10}$$

- Combine E949 & E787

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$

» errors for 68% C.L.

	E787		E949
N_K (10^{12})	5.9		1.8
Candidate	E787A	E787C	E949A
S_i / b_i	50	7	0.9
$W_i=S_i/(S_i+b_i)$	0.98	0.88	0.48
BG Prob.	0.006	0.02	0.07



E949(02) = combined E787&E949

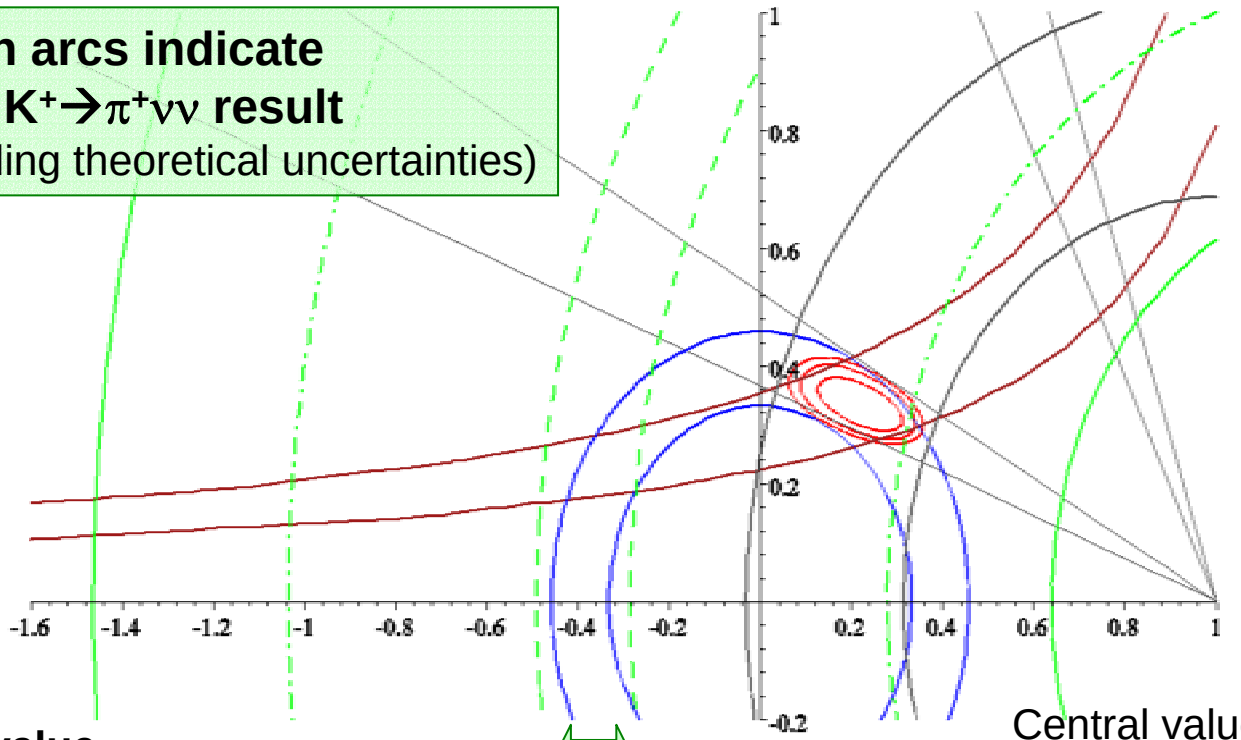
E949 projection with 60 weeks run (assuming current BR value)

Impact on Unitary Triangle

- Contour in ρ-η plane

by the courtesy of G. Ishidori

Green arcs indicate this $K^+ \rightarrow \pi^+ \nu\nu$ result
(including theoretical uncertainties)



Central value

68% interval

90% interval

Central value off the "SM"
→ **Need more data!!**

Conclusions

- E949 successfully ran as a first step
  - Upgrade to E787 successfully
  - 12 weeks, N_K=1.8x10^{12}
- Likelihood applied to evaluate branching ratio
- E949 (02) has observed an additional candidate
- Combining the E787 and E949 results,

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \ (68\% C.L.)$$

- Prospects
  - E949 PNN2 analysis (Pπ+ < 195 MeV/c region) in progress
  - Further E949 run?
    - We are ready to complete the experiment and waiting for funding !!

Extras

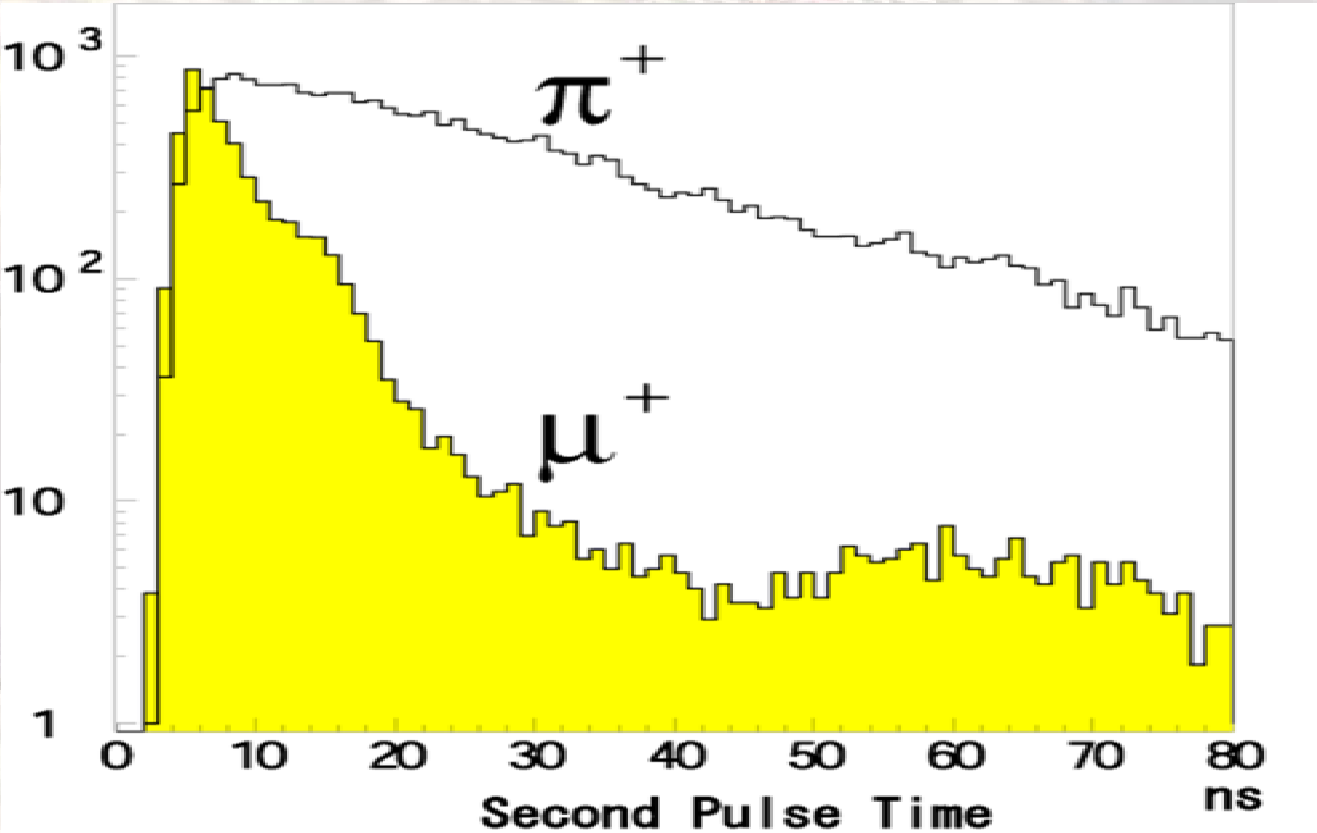
Verify background prediction

- Loosen cuts and look in M x N times larger box
  - Two independent cuts for one background
    - For ex., Photon Veto, TD(NN function), and KINematics
- Compare prediction and observed # of events

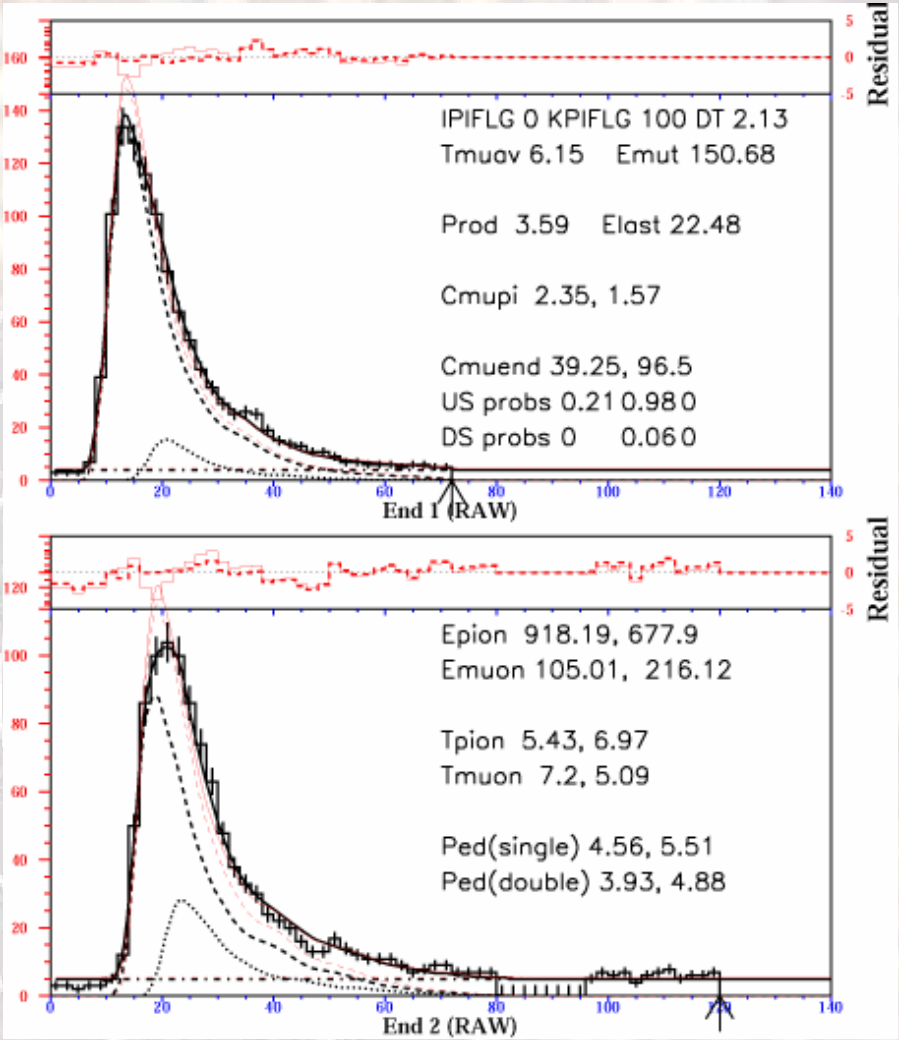
$K\pi 2$	PV x KIN	10 x 10	20 x 20	20 x 50	50 x 50	50 x 100
	Observed	3	4	9	22	53
	Predicted	1.1 ± 0.18	4.9 ± 0.6	12.4 ± 1.3	31.1 ± 3.1	62.4 ± 5.6
$K\mu 2$	TD x KIN	10 x 10	20 x 20	50 x 50	80 x 50	120 x 50
	Observed	0	1	12	16	25
	Predicted	0.35 ± 0.03	1.4 ± 0.1	9.1 ± 0.6	14.5 ± 1.0	21.8 ± 1.5
$K\mu\nu\gamma$	TD x KIN	10 x 10	20 x 20	50 x 20	80 x 20	80 x 40
	Observed	1	1	4	5	11
	Predicted	0.31 ± 0.09	1.3 ± 0.4	3.2 ± 1.0	5.2 ± 2.2	10.4 ± 2.8

Second pulse time for π and μ

- Case π^+ : μ^+ from $\pi \rightarrow \mu\nu$ decay
- Case μ^+ : accidental or pulse fluctuation



Pulse fitting in the π^+ stopping counter

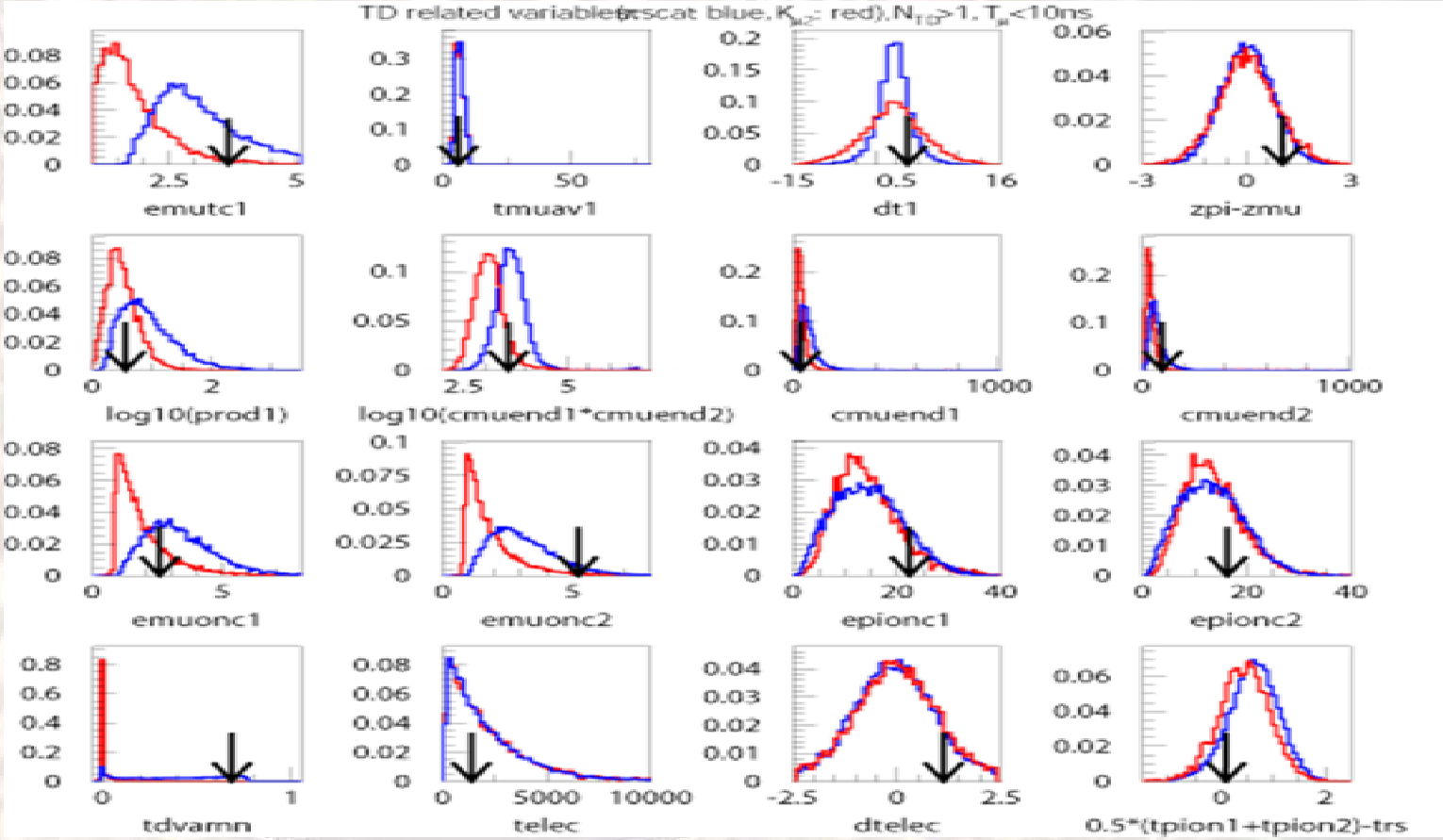


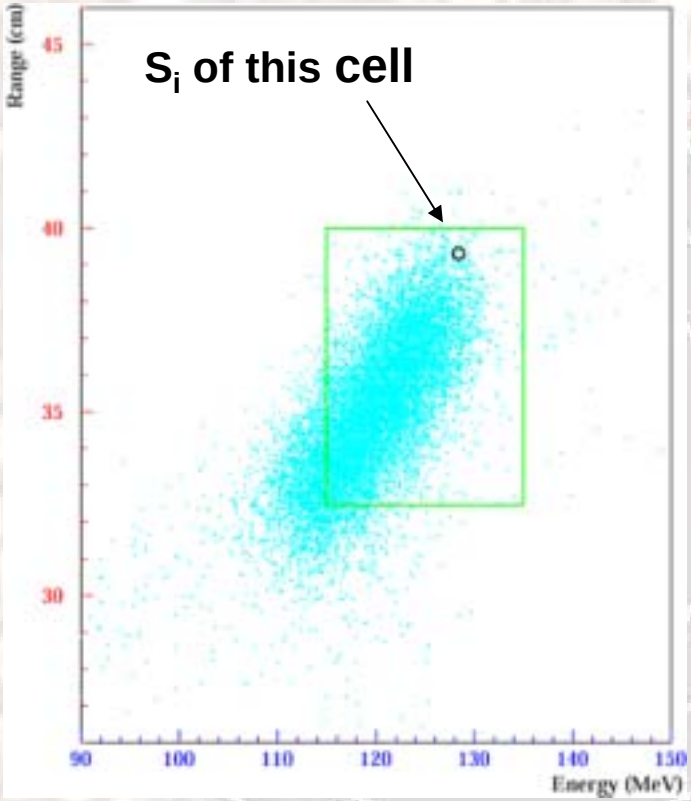
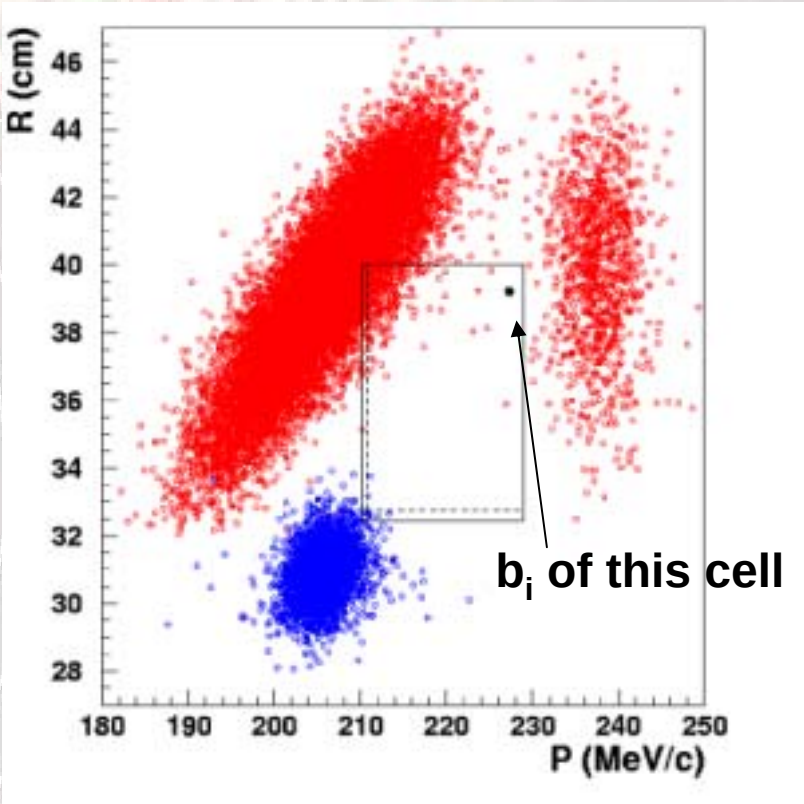
TD properties of the candidate

- Plots with π^+ and μ^+ samples

Blue: π^+ (fitted $\pi \rightarrow \mu$ time<10ns)
Red : μ^+

Arrows show the candidate event



S_i and b_i for the candidate cell

- Signal $S_i = 5.3 \times 10^{-5}$, with $BR(K^+ \rightarrow \pi^+ \nu\nu) = 1.47 \times 10^{-10}$
- Background $b_i = 5.7 \times 10^{-5}$ ➔ $W_i = S_i / b_i = 0.9$