Rare Kaon Decay Results From E949 At BNL: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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Motivation is clear and simple

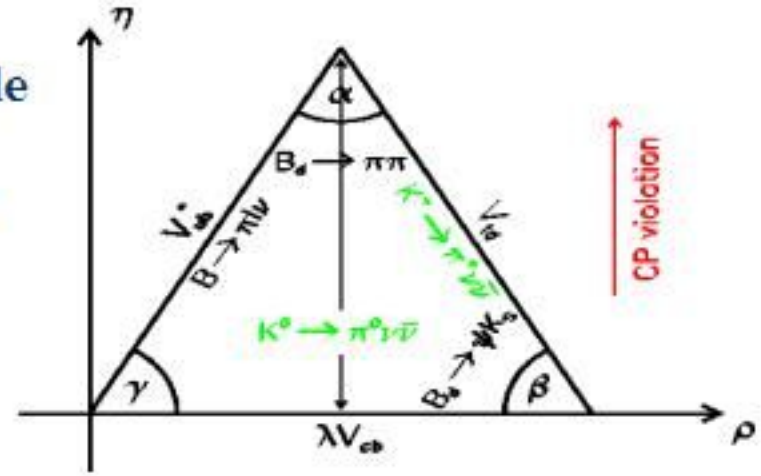
- Use $K^+ \to \pi^+ \bar{\nu} \nu$ and $K^0 \to \pi^0 \nu \nu$ to measure the CPV related elements

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

- To construct the K unitarity triangle and confirm the "golden" relation which is valid in the SM and MFV.

$$(\sin 2\beta)_{\pi \nu \bar{\nu}} = (\sin 2\beta)_{J/\Psi K_S}$$

A.J. Buras *et.al* hep-ph/0405132

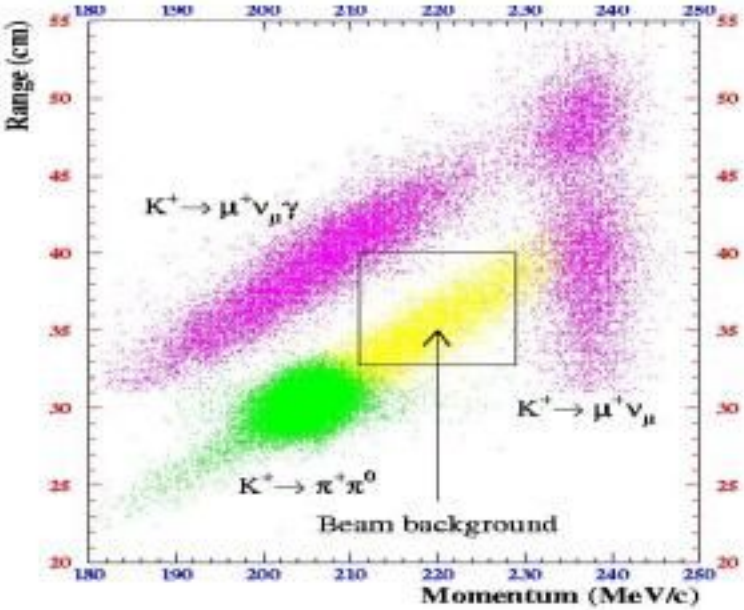


Experiment is challenging

Standard Model: $Br(K^+ \to \pi^+ \nu \bar{\nu}) = (0.79 \pm 0.12) \times 10^{-10}$

- Weapons needed to suppress background by 10^{10} in order to see the signal.

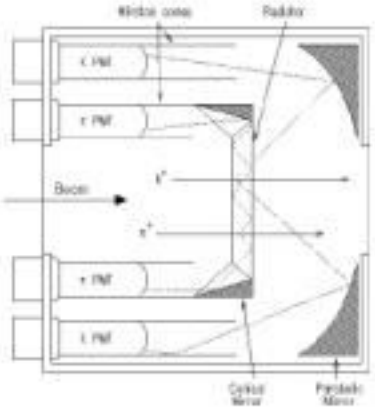
Process	Events
$K^+ \to \mu^+ \nu_\mu$	6343000000
$K^+ \to \pi^+ \pi^0$	2113000000
$K^+ \to \mu^+ \nu_\mu \gamma$	55000000
Beam bkg	25000000
$K^+ n \to K^0 p$, $K^0 \to \pi^+ l \nu$	46000
$K^+ \to \pi^+ \nu \bar{\nu}$	1

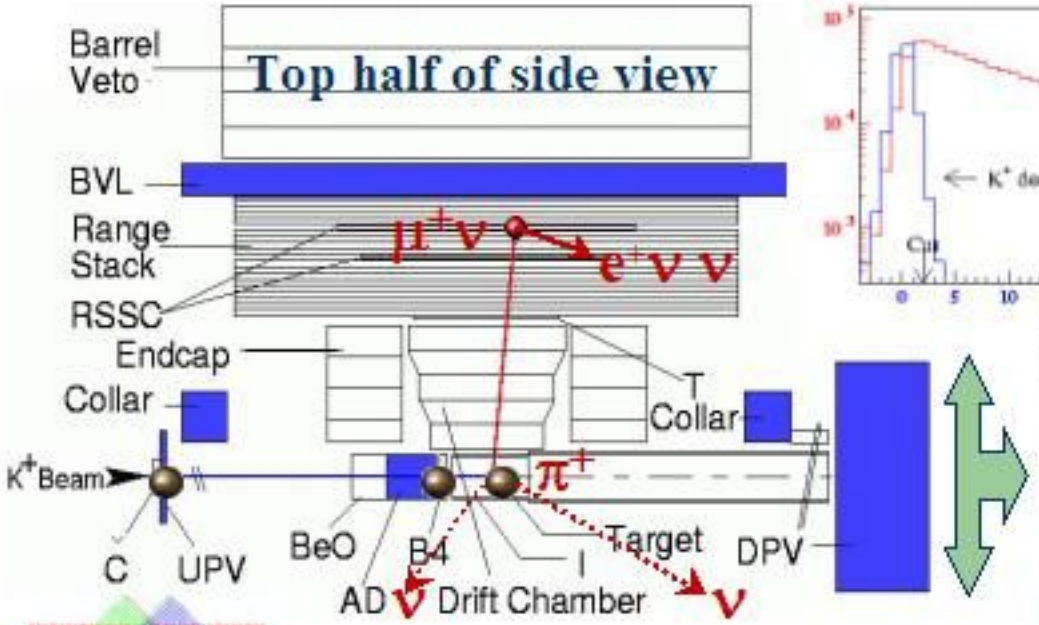


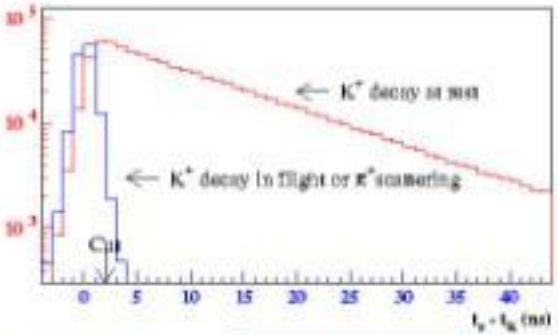
- Where can we find such a "WMD"?

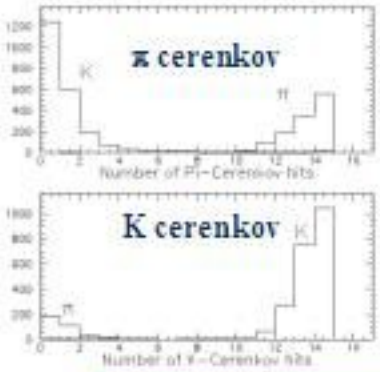
BNL-E949 detector

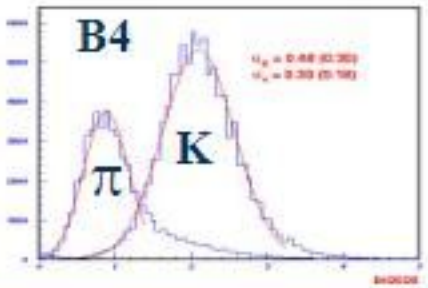
-- Rejecting beam backgrounds

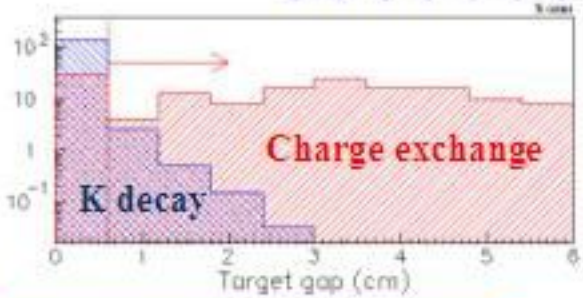








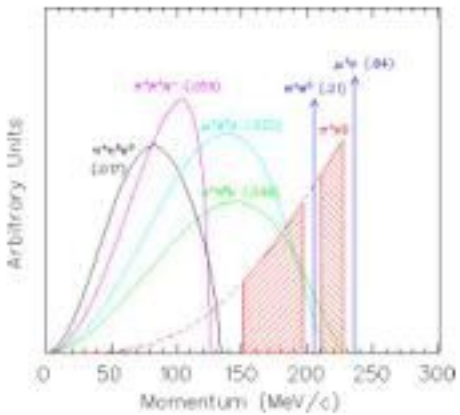


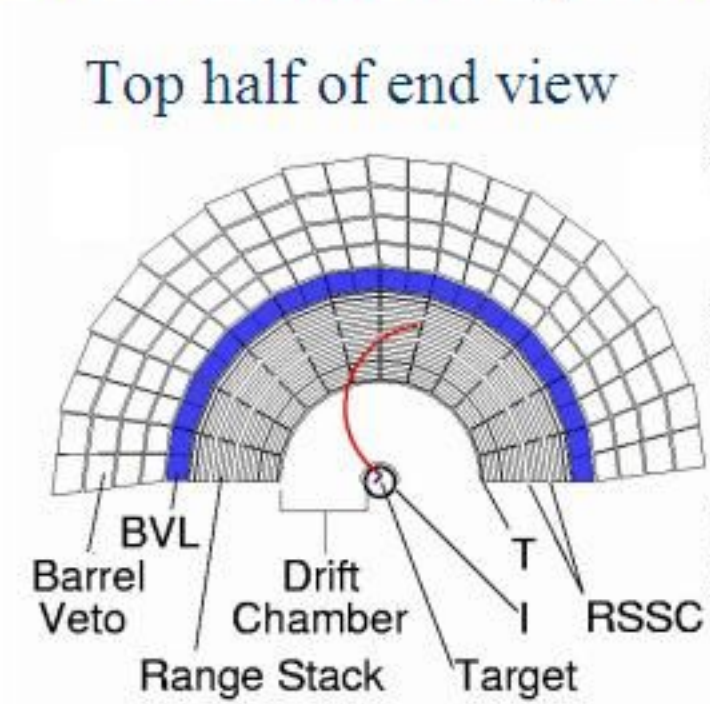


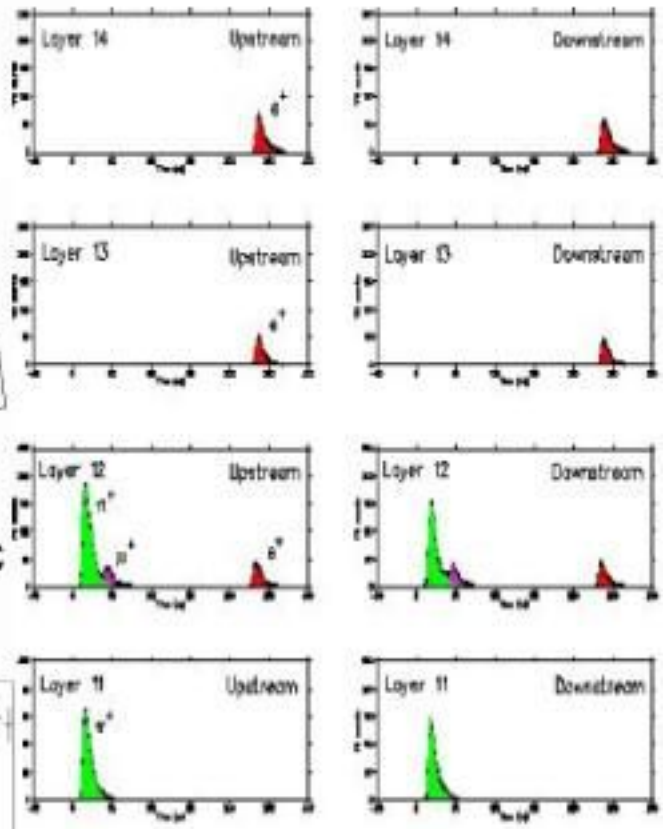
Beam backgrounds include pion scattering, kaon decay-in-flight, and charge-exchange reactions.

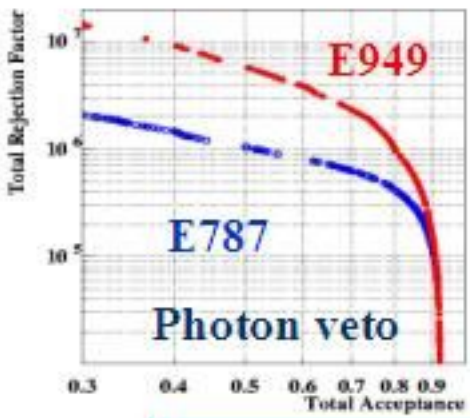
BNL-E949 detector

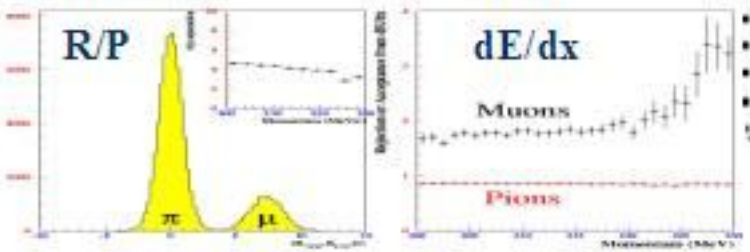
-- Powerful and redundant particle ID











π-ID from its decay chain.

Resolutions: $\Delta P/P \sim 1.1\%$; $\Delta R/R \sim 3.0\%$; $\Delta E/E \sim 1.0\%/\sqrt{E}$.

Rejections: $\sim 10^5$ for μ; $\sim 10^6$ for photon with 4π sr coverage.

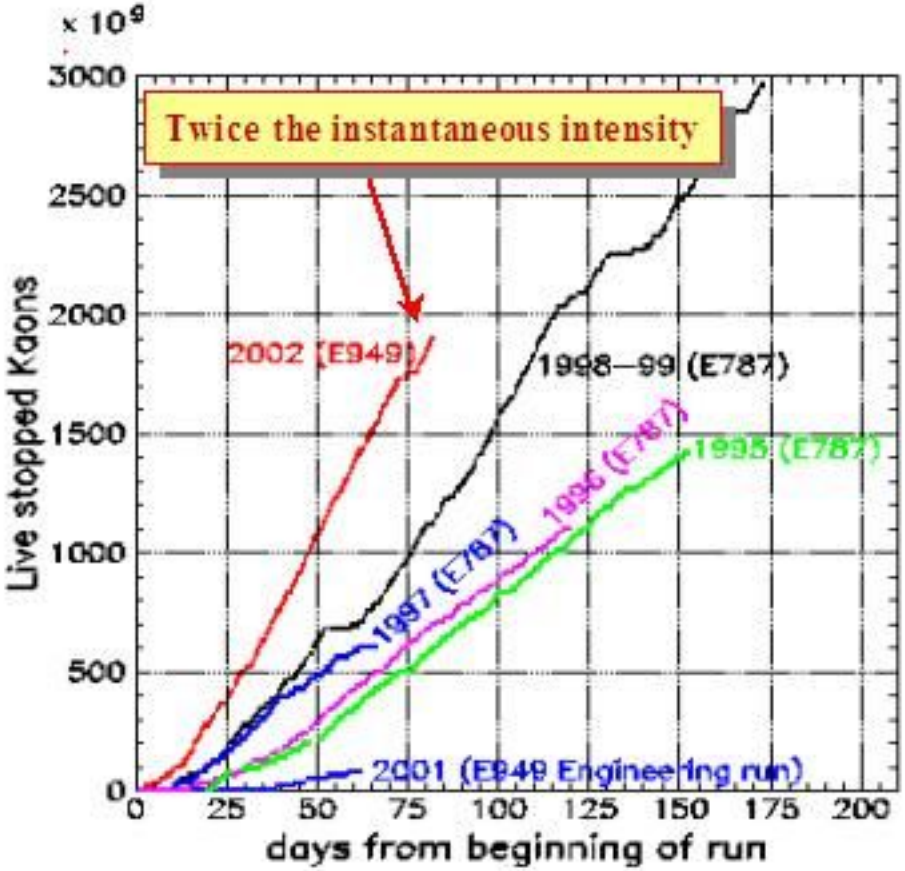
This is a team effort!

16 institutes and universities in 4 countries.

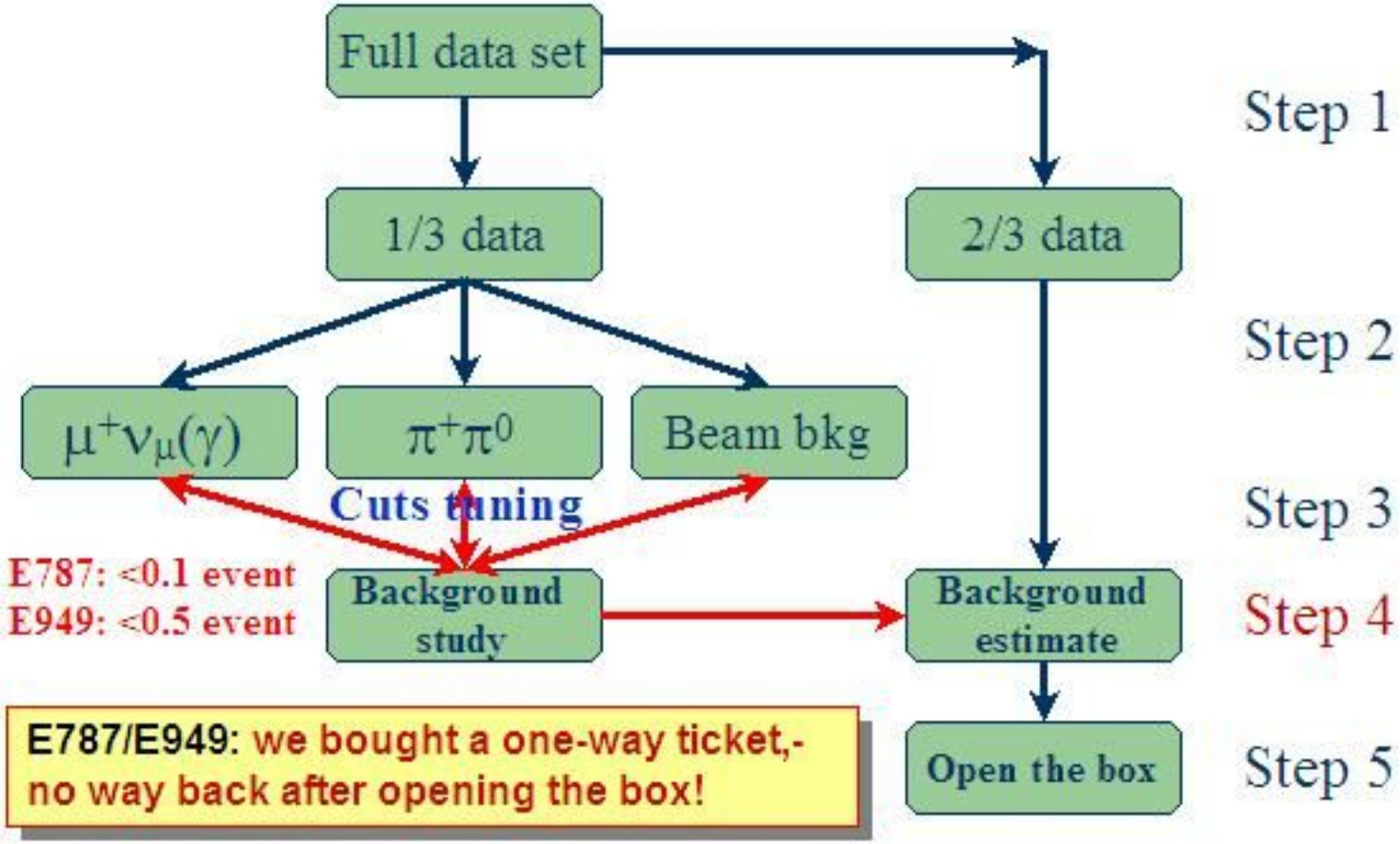
BNL/FNAL/SBU/UNM, U.S.A
IHEP/INR, Russia
Fukui/KEK/Kyoto/NDA/Osaka, Japan
TRIUMF/UA/UBC, Canada

…more than 60 physicists from 6 countries.

Many thanks to BNL-AGS people



Unique Strategy for data analysis



E787/E949: we bought a one-way ticket,- no way back after opening the box!

Background suppression

Cut / Bkg	Kinematics cuts(p/R/E)	Particle ID(K/π/μ)	Photon veto	Timing cuts
$K^+ \to \mu^+\nu_\mu\gamma$	√	√	√	
$K^+ \to \pi^+\pi^0$	√		√	
Beams		√		√
$K^+ n \to K^0 p$, $K^0 \to \pi^+ l\nu$			√	√

Backgrounds inside the box

Items	E949	E787
Nk(10^{12})	1.8	5.9
$K^+ \to \mu^+\nu_\mu\gamma$	0.068 ± 0.011	0.062 ± 0.045
$K^+ \to \pi^+\pi^0$	0.216 ± 0.023	0.034 ± 0.007
Beams	0.009 ± 0.003	0.025 ± 0.016
$K^+ n \to K^0 p$, $K^0 \to \pi^+ l \nu$	0.005 ± 0.001	0.025 ± 0.008
Total bkg (evts)	0.298 ± 0.026	0.146 ± 0.049

❖Errors are statistical only.

What could be our nightmares?

A 0.3 event background estimated, but more than 3 events observed!

Underestimating background because…

- **Correlation between two bifurcated cuts.**

  It can happen if an observable is used in both CUT1 and CUT2 categories, spoiling the independence of the bifurcated analysis.

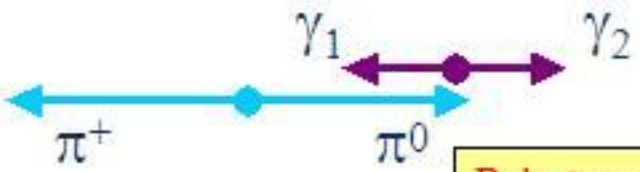
- **Appearance of pathology backgrounds.**

  It rarely happens but can appear thru a loophole. Hand-scanning the events outside the box is the only way to spot the problem.

For example…

Example1:
Correlation between two cuts

A new geometrical cut that gained 10% more rejection again π^0 was found to



Reject any event with a photon in opposite side.

cause trouble in the 1/3 outside-the-box study: N(obs.)~2.0 N(pred.)

Reason: a new cut was developed that used the direction of the π^+ to place a tighter requirement again photons
Remedy: remove this cut & retune PV.

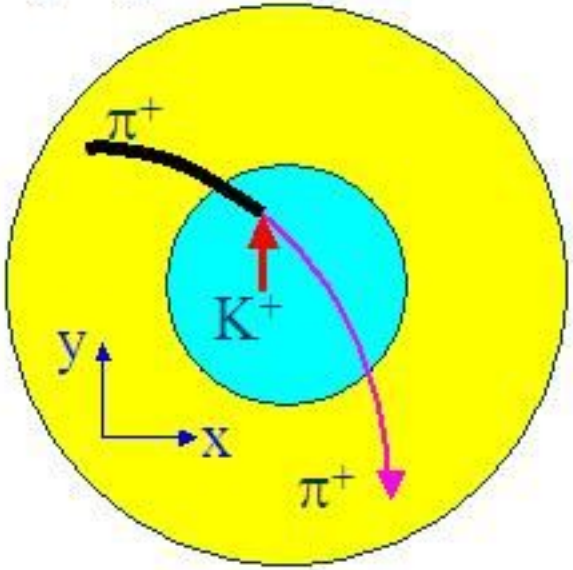
Loosen PV x KIN	Obs.	Pred.
20 x 20	3	1.8
20 x 50	8	3.0
50 x 50	22	11.1

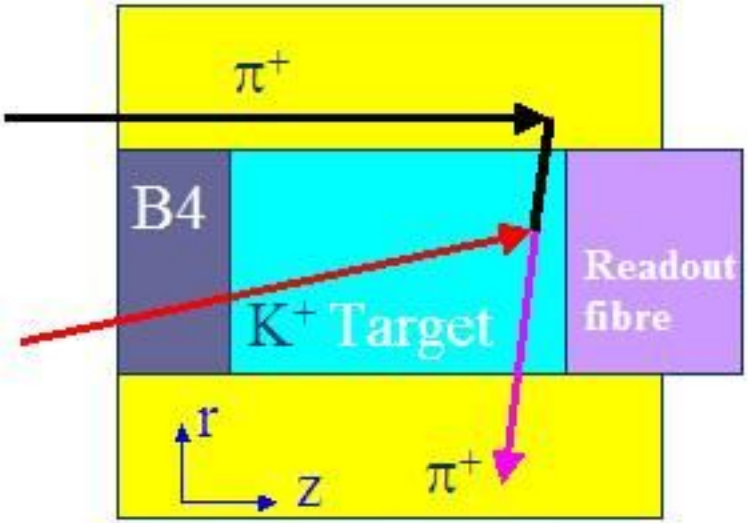
retune PV

Loosen PV x KIN	Obs.	Pred.
20 x 20	4	4.9
20 x 50	9	12.4
50 x 50	22	31.1

Example 2:
Pathology background

Pions scattered back into the target overlaying a non-decaying kaon can make a fake signal.





Reason: track reconstruction only down to the kaon decay vertex.
Remedy: check the hits in the opposite direction of the track.

Backgrounds outside the box

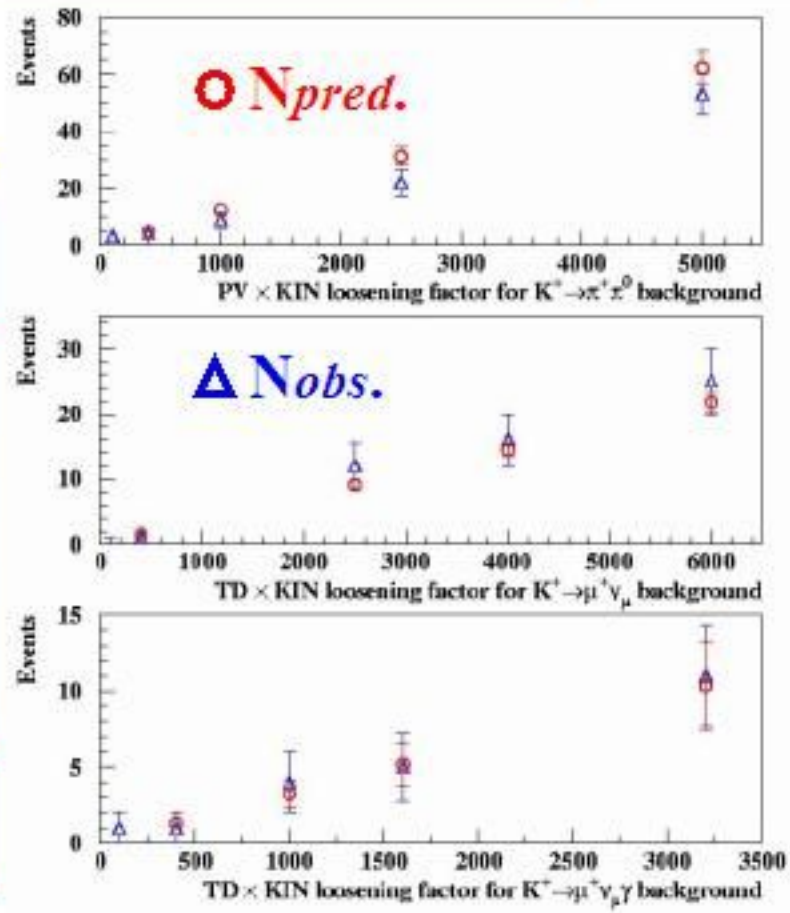
Motivations:

1) To check the correlations;
2) To estimate systematic errors.

Fit $N_{obs.} = c\, N_{pred.}$

Bkg.	c	χ^2 Prob.
$\pi^+\pi^0$	$0.85^{+0.12}_{-0.11}$	0.17
$\mu^+\nu_\mu$	$1.15^{+0.25}_{-0.21}$	0.67
$\mu^+\nu_\mu\gamma$	$1.06^{+0.35}_{-0.29}$	0.40

Deviations of c from unity give the systematic errors.



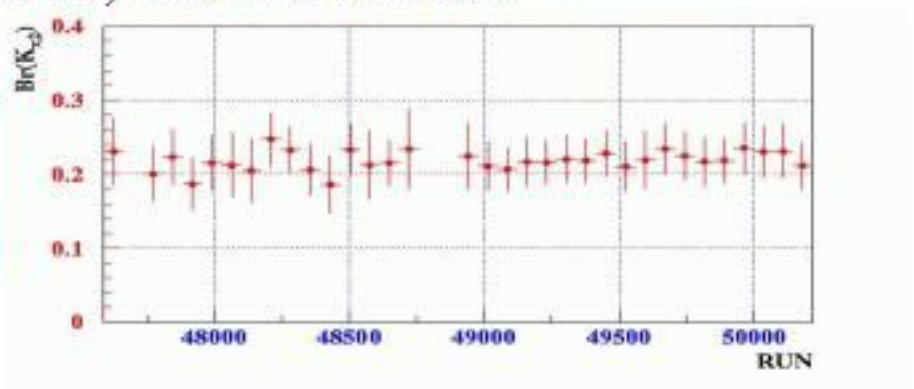
Acceptance

- Phase space and nuclear interaction effects from Monte Carlo.
- Acceptance loss due to PID, photon veto, timing and other kinematics cuts directly measured from data.

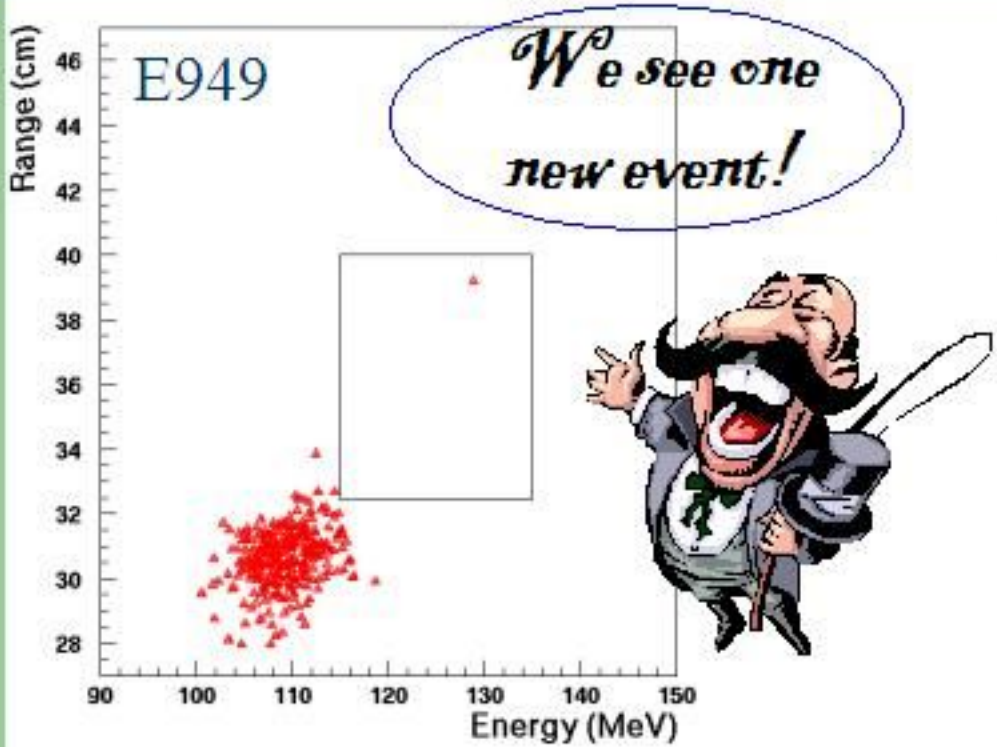
E949 acceptance: 0.0022 ± 0.002
E787 acceptance: 0.0020 ± 0.002

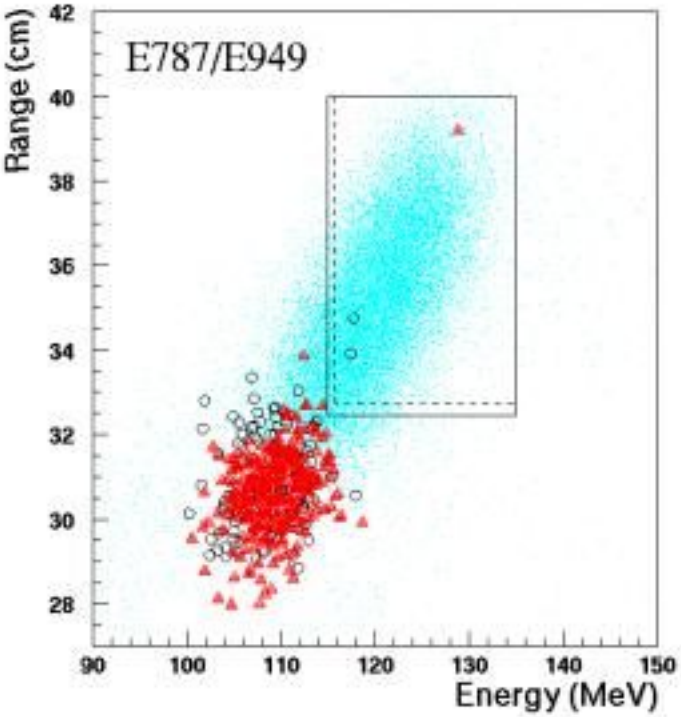
- Verification from $B(K^+ \rightarrow \pi^+\pi^0)$ measurements.

$Br(K^+ \rightarrow \pi^+\pi^0)$=0.219±0.005
P.D.G value is 0.211±0.001



Open the box and guess what?





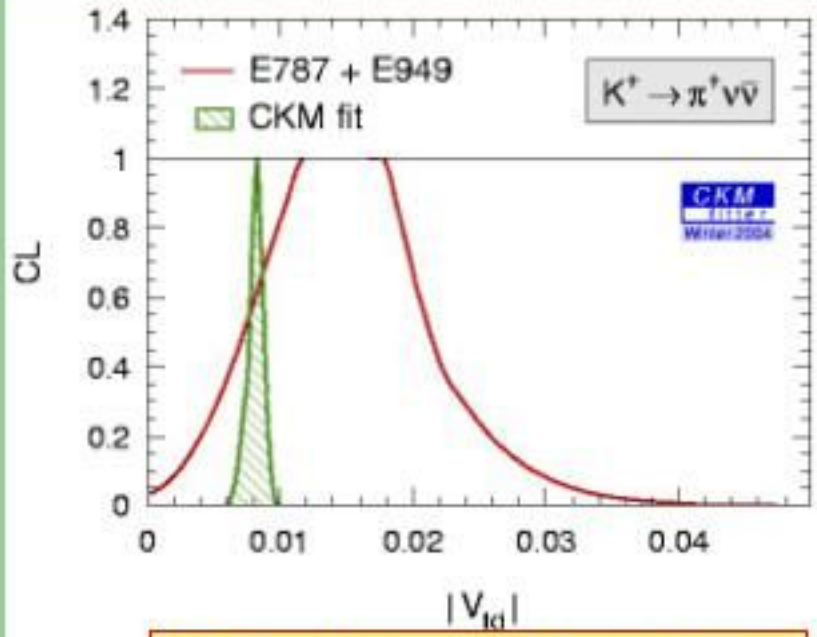
Branching Ratio Result

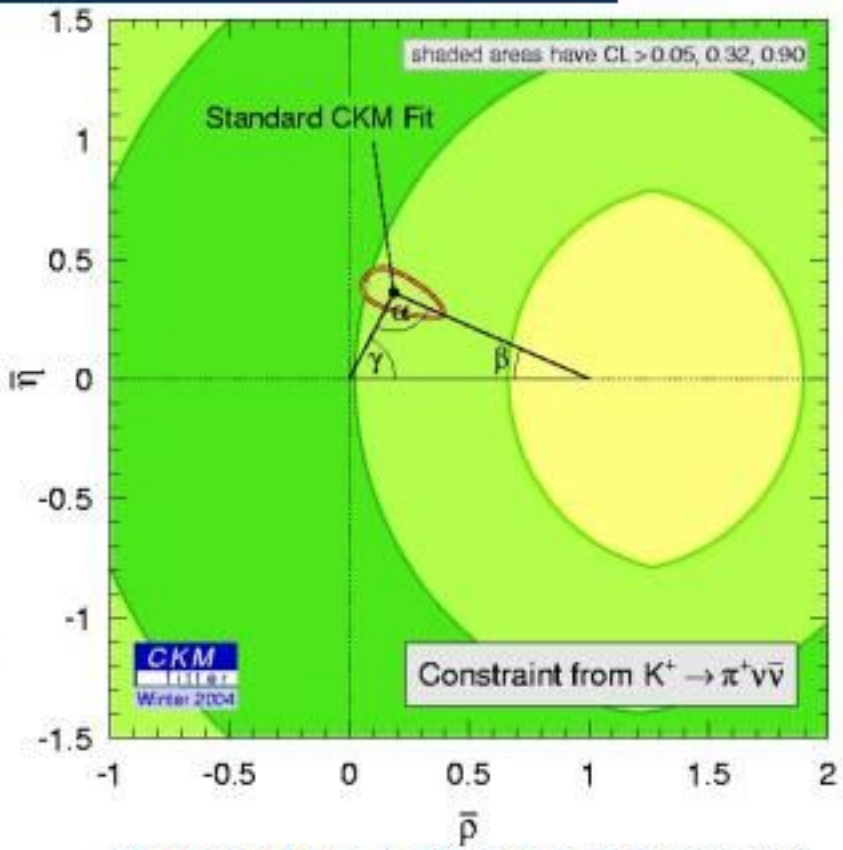
To make best use of our knowledge of the signal and the background distributions inside the box, we define cells inside the box.

B_i: background of cell containing candidate.
S_i : $Br \times A_i \times N_K$.
N_K: Stopped K^+'s.
A_i: acceptance in a cell.
Br: branching ratio.
W: $S/(S + b)$.

	E949	E787	
Candidate	E949A	E787A	E787C
S/b	0.9	50	7
W	0.48	0.98	0.88
Br	$(1.47^{+1.30}_{-0.89})\times10^{-10}$		

Impact on CKM matrix





- More data needed for reducing the uncertainty.
- New neutral kaon experiments (for example KOPIO) expected for further justification.

Many thanks to A. Höcker & J. Ocariz *et al*
The CKM fitter group, hep-ph/0406184

Summary

- A successful run of E949 with a factor of two more beam intensity as in E787.
- A new candidate event observed for $K^+ \to \pi^+ \nu \bar{\nu}$, leading to a combined result from E787/E949,

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

hep-ex/0403036

$\sim 2 \times Br(K^+ \to \pi^+ \nu \bar{\nu})_{SM}$, if $(\sin 2\beta)_{\pi \nu \bar{\nu}} = (\sin 2\beta)_{J/\Psi K_S}$.

Statistical fluctuation or evidence of new physics?