Measurement of the decay $K^+ \to \pi^+ \nu\bar{\nu}$

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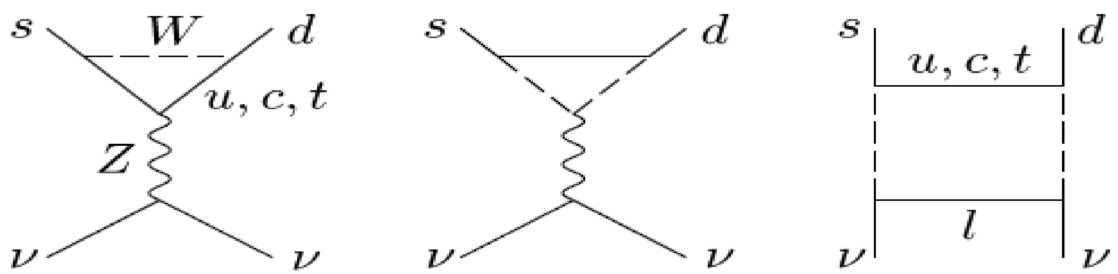
$K \to \pi\nu\bar{\nu}$ in the SM



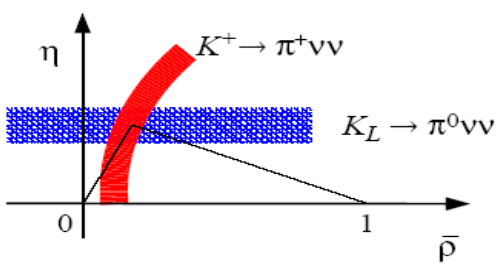
Standard Model (*Buras et al., Mescia and Smith, Brod and Gorbahn*):

$$B(K_L^0 \to \pi^0\nu\bar{\nu}) = 1.8\,x10^{-10}\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 = 2.76 \pm 0.40\,x10^{-11}$$

$$B(K^+ \to \pi^+\nu\bar{\nu}) \sim 1.0\,x10^{-10}A^4\left[\eta^2 + (\rho_0 - \rho)^2\right] = 8.5 \pm 0.7\,x10^{-11}$$

$$\mathrm{Im}\,\lambda_t = \mathrm{Im}V_{ts}^*V_{td} = \eta A^2\lambda^5$$

Golden Relation: $\sin(2\beta)_{\psi K_S} = \sin(2\beta)_{K\to\pi\nu\bar{\nu}}$



$K \to \pi\nu\bar{\nu}$

New Physics: *Model-Independent Description*

(Buras, Isidori, et al.)

L_{SM} ~ Renormalizable part of an effective field theory :

$$L_{EFT} = L_{SM} + \Sigma \frac{\lambda}{\Lambda^2}$$

Main Issues: Cutoff scale Λ [TeV], Symmetries

Rare K Decays can probe the flavor structure of the new physics at very high mass scales.

For measurement precision $\quad \mathrm{P} = \dfrac{\sigma(B)}{B_{SM}(K_L^0 \to \pi^0\nu\bar{\nu})} = 10\%$:

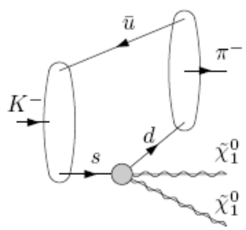
$$\frac{\Lambda}{\sqrt{\mathrm{Im}\,\lambda_{sd}}} > \frac{405}{\sqrt{P}}\ \mathrm{TeV}\ \ (90\%\mathrm{C.L.}) \longrightarrow \Lambda \geq 1280\mathrm{TeV!}$$

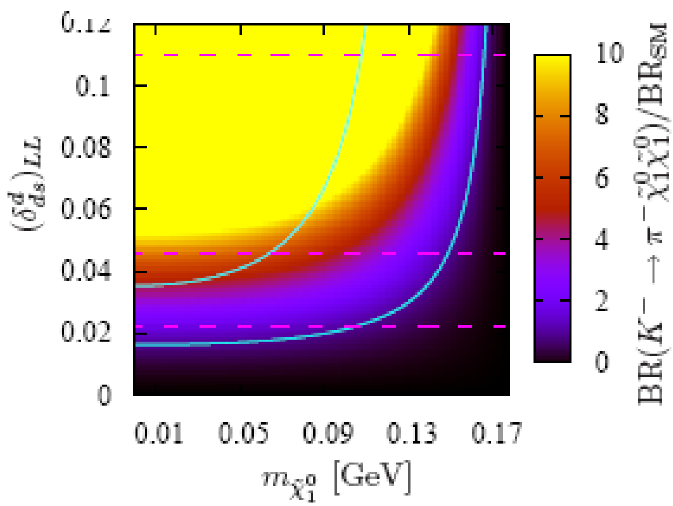
$K \to \pi\nu\bar{\nu}$: Great Discovery Potential

Two Examples

SUSY: Rare meson decays into light neutralinos

$K^+ \to \pi^+\nu\bar{\nu} \to$ N x SM



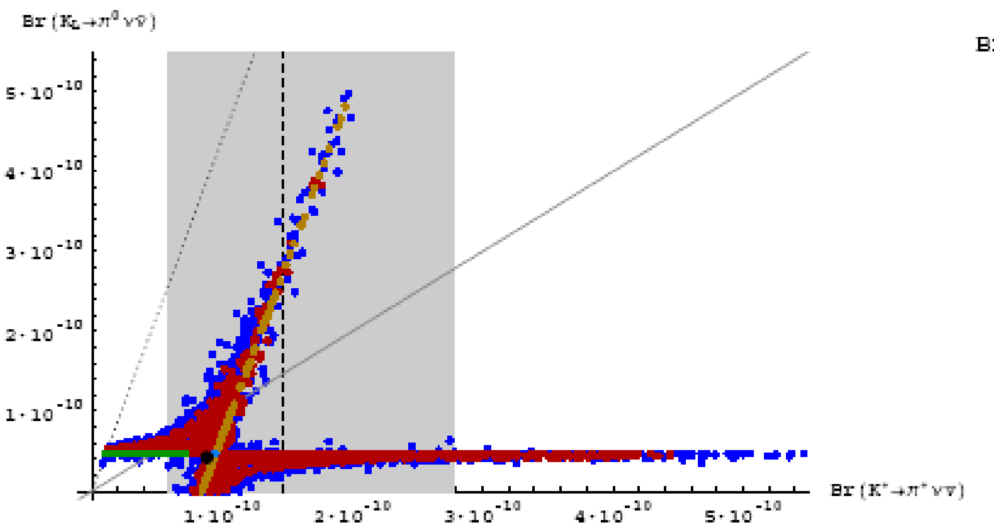


H. K. Dreiner ***et al.*** Bonn-TH-2009-04

Minimal Flavor Violation e.g.

Littlest Higgs Model with T-parity

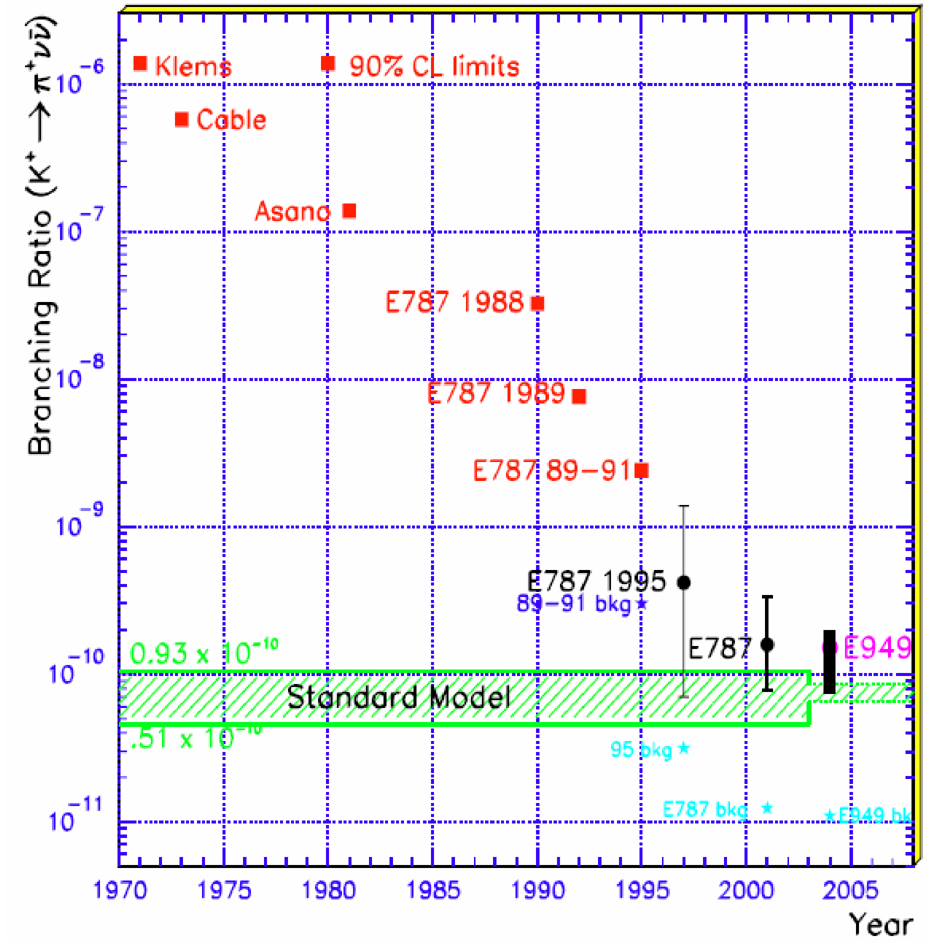
$B(K_L^0 \to \pi^0\nu\bar{\nu})$ *vs.* $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$



M. Blanke, *et al.*,arXiv:hep-ph/0610298.

Experiments

$$E949: \quad B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

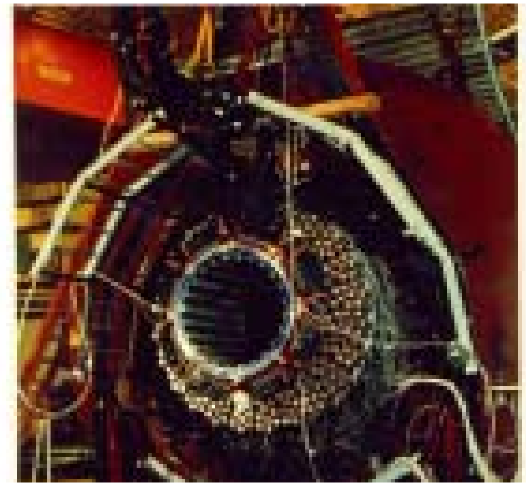


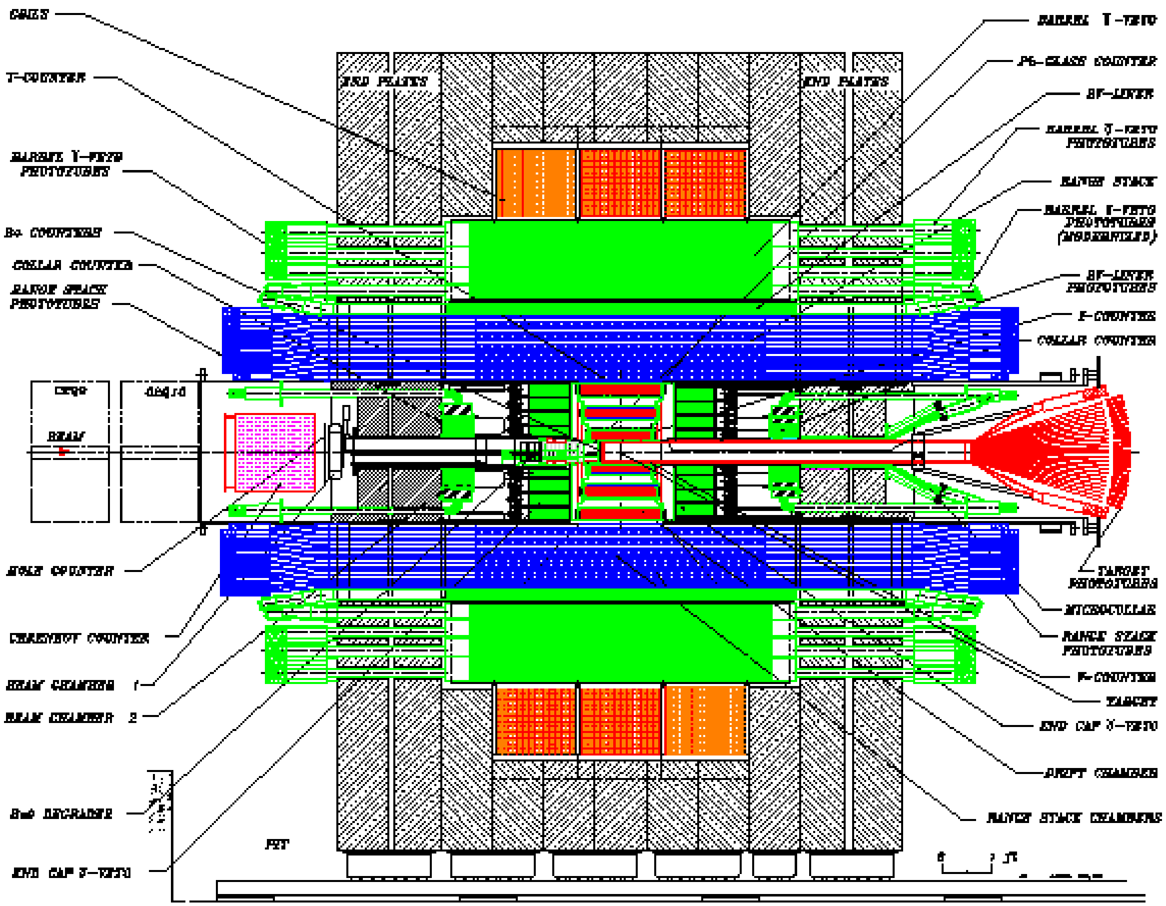
7 events observed

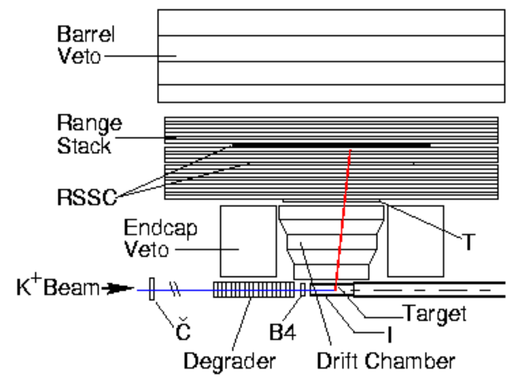
BNL E949

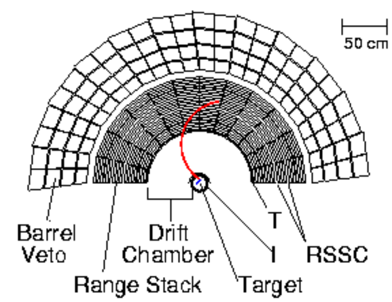
Measurement of

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









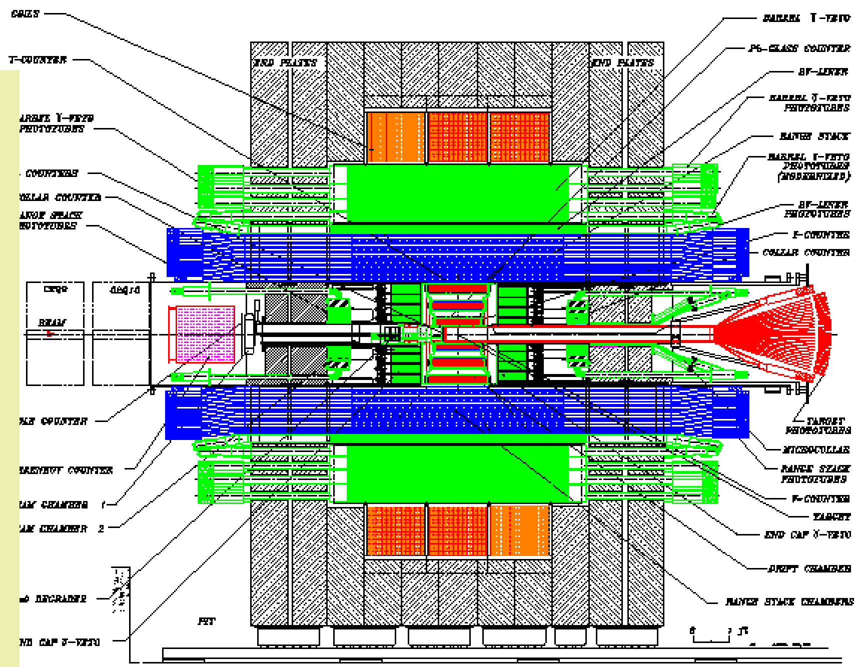
BNL E787/949 Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$

CANADA-CHINA-JAPAN-RUSSIA-USA Collaboration:

Institute for Nuclear Research **(Moscow),** Institute for High Energy Physics **(Protvino),** University of **New Mexico**, **Princeton** University, **Brookhaven National Laboratory,** **TRIUMF**, University of **British Columbia**, **Tsinghua** University (Beijing), **Stony Brook** University, **Fermilab**, **Kyoto** University, **KEK,** University of **Alberta**, **Fukui** University, **Osaka** University, **National Defense Academy** (Japan)

Advanced Technologies:

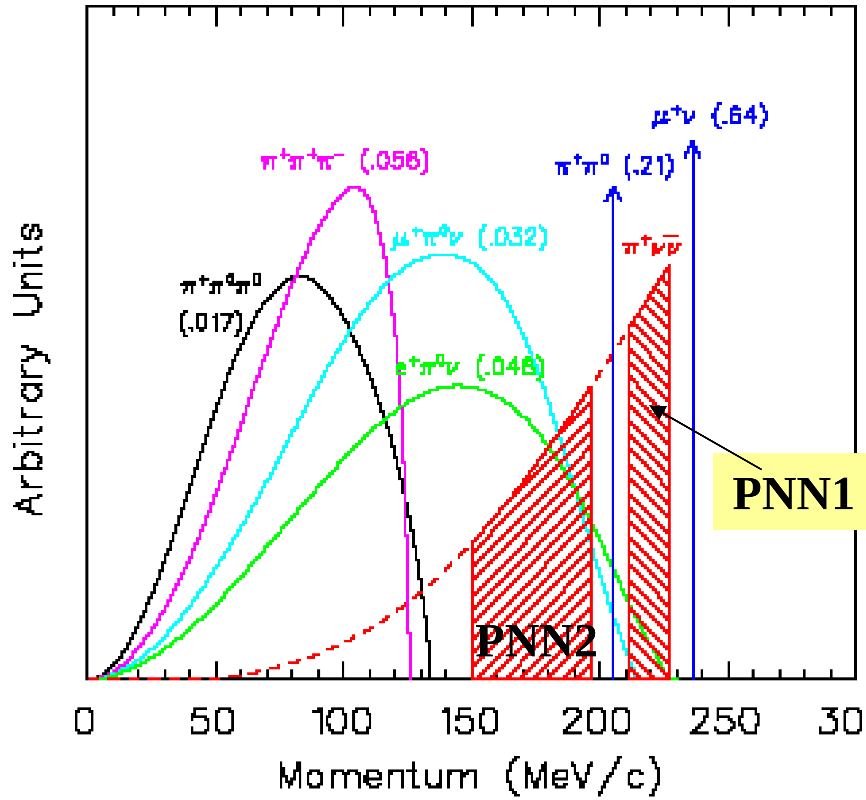
- **Highest Efficiency Detection**
- **Low mass central tracking chamber - inflated cathodes**
- **500 MHz digitizers**
- **Scintillating fiber target**
- **Pure CsI calorimeter**
- **"Blind Analysis"**



Special Features of Measuring

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

Background processes exceed signal by $>10^{10}$

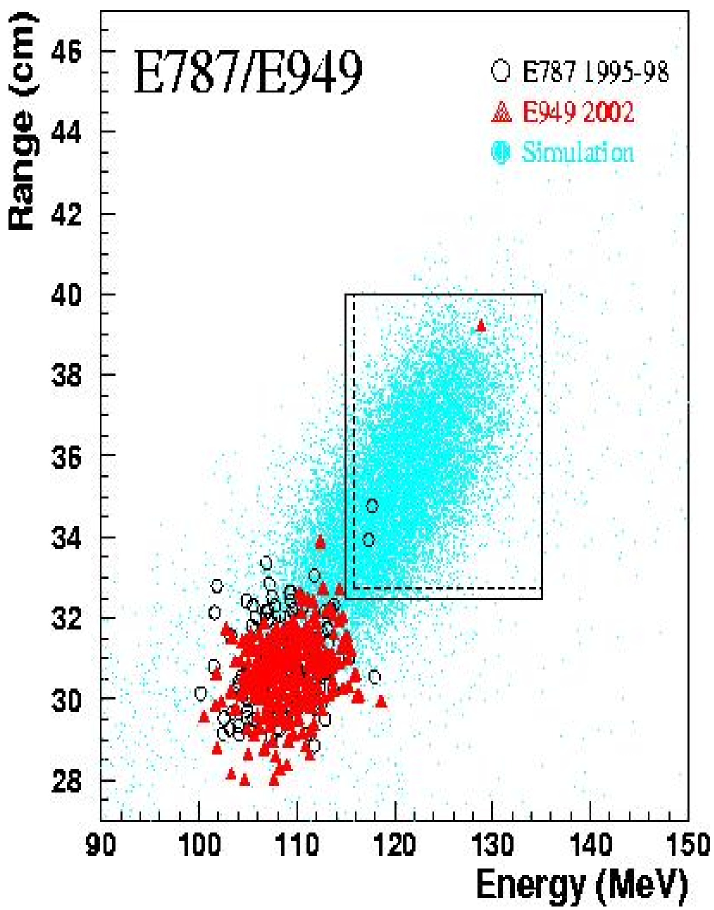


- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds *from data*: dual independent cuts
  - * Use “Blind analysis” techniques
  - * Test predictions with “outside-the-box” measurements
- Evaluate candidate events with S/N function

Previous measurements E787/E949

PNN1: Above $K_{\pi 2}$ peak: 3 events

$$B(K^+ \rightarrow \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$



PNN2: Below $K_{\pi 2}$ peak: *limit*

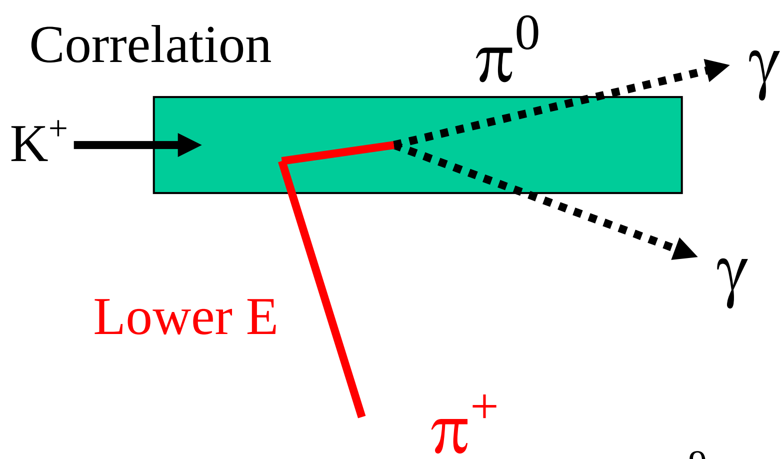
$$B(K^+ \rightarrow \pi^+ \nu\nu) < 2.2 \times 10^{-9}$$

1 event observed

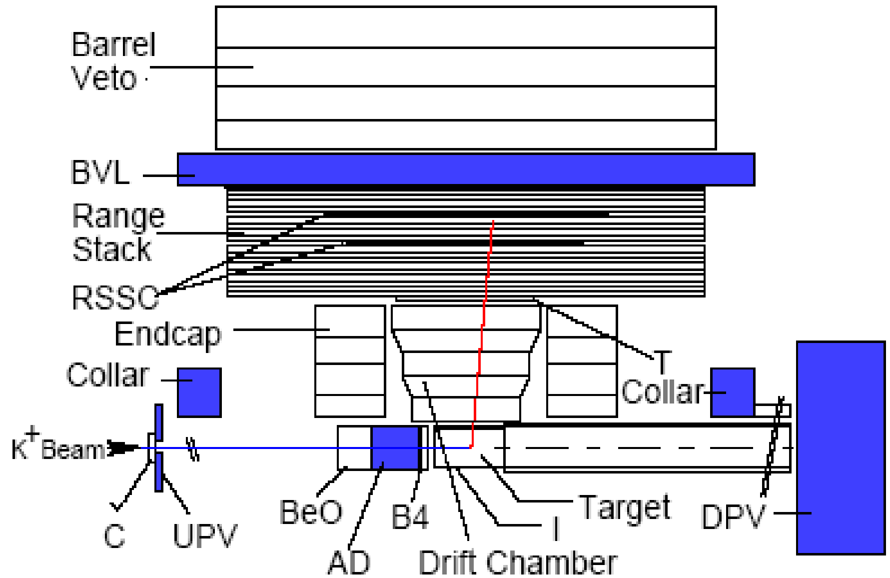
Bkg=1.22±0.24 events

PNN2 Primary Background:

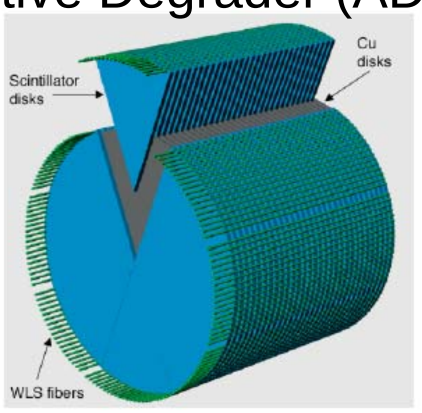
$$K^+ \rightarrow \pi^+ \pi^0 \quad (K_{\pi 2})$$

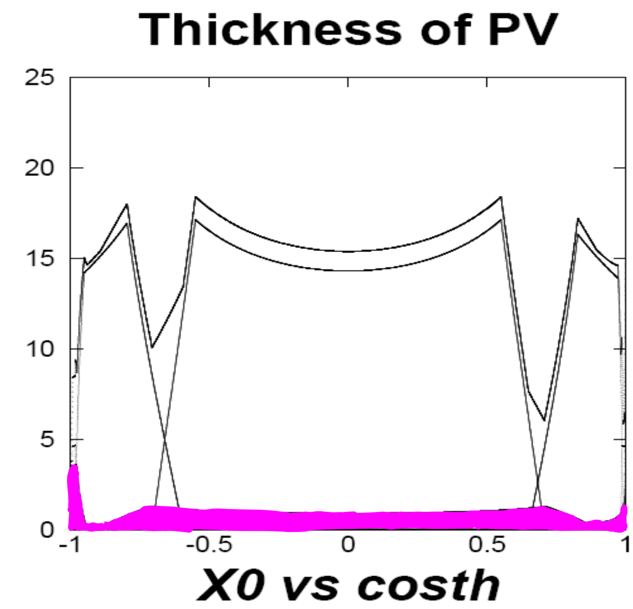


E787 → E949; access to PNN2

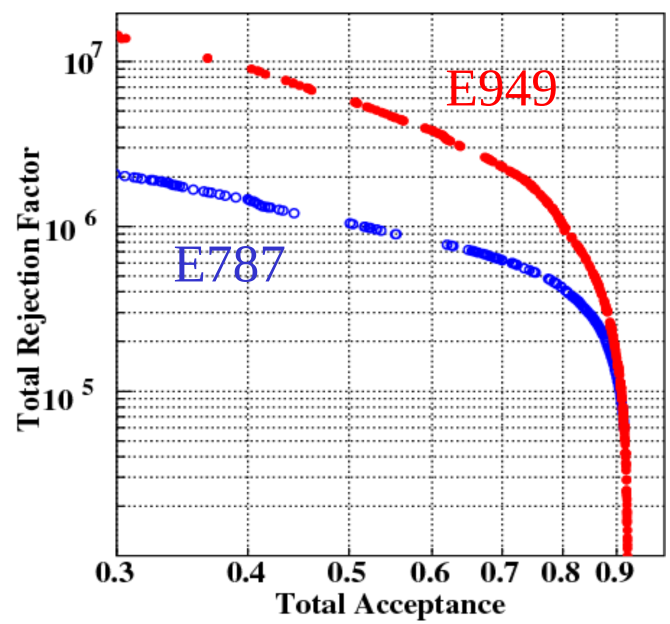


Active Degrader (AD)

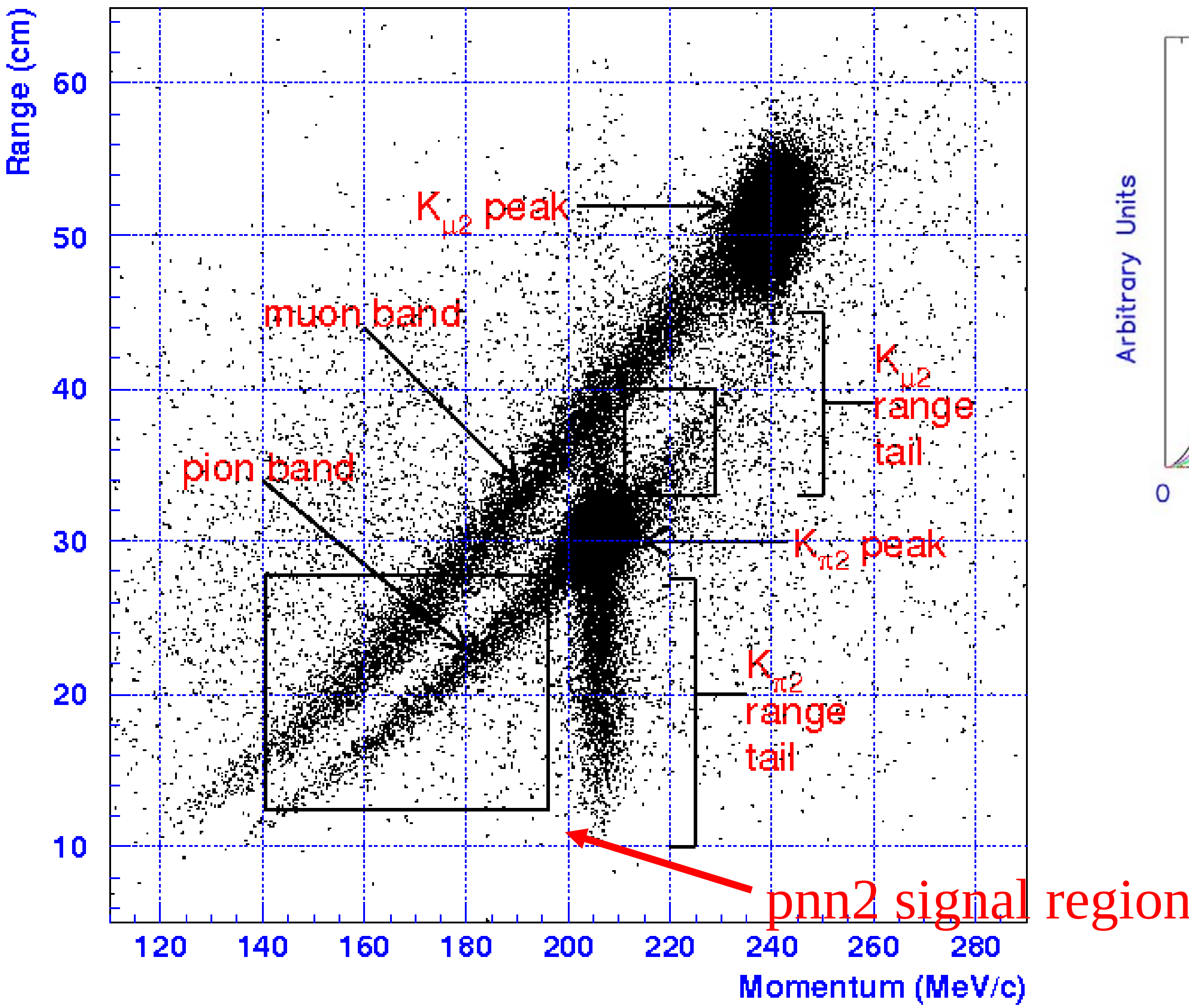


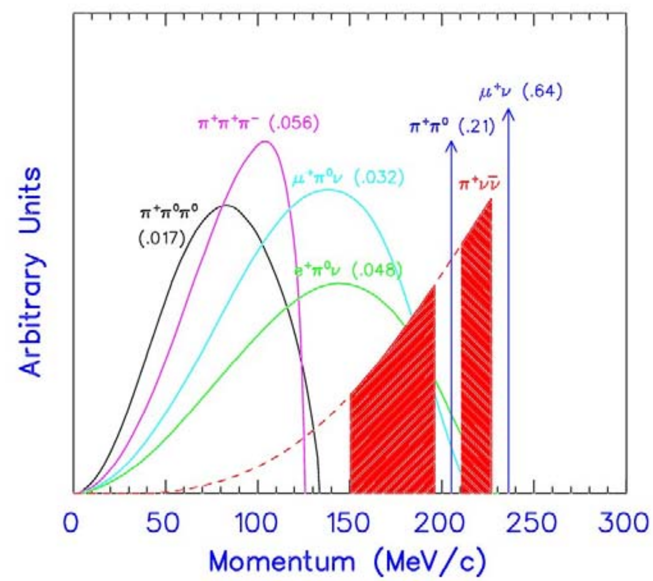


π^0 Veto power



Before cuts

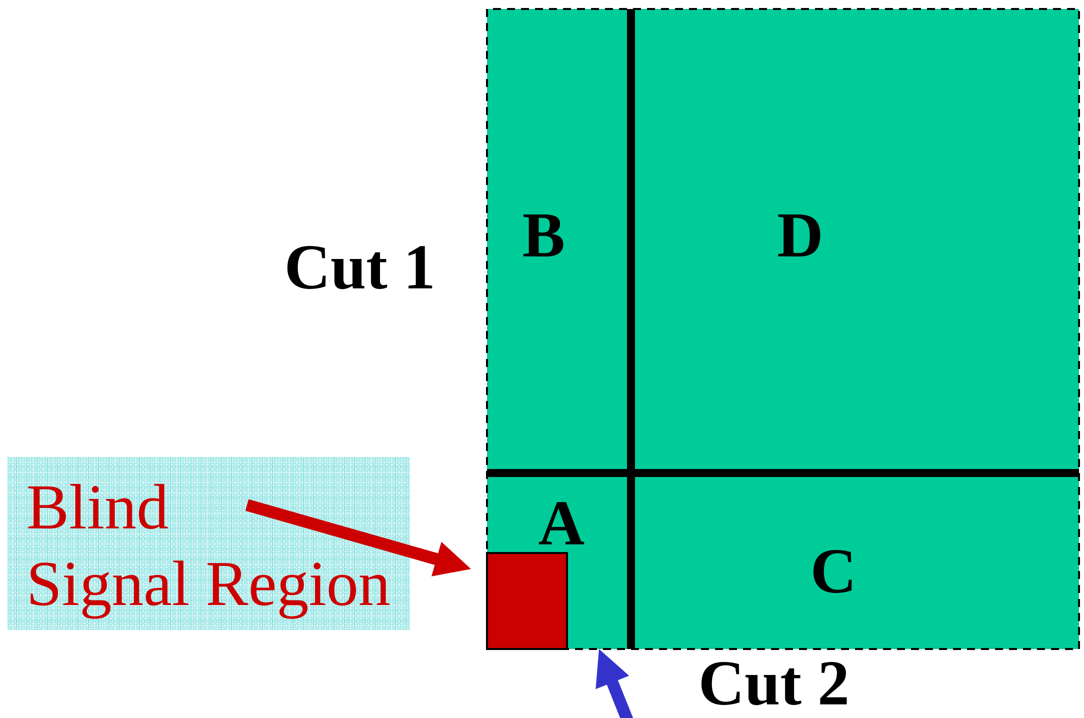




- Kinematics
- π→μ
- Extra particles
- Photon veto
- Kink cuts

Estimating Backgrounds
Dual-Cut BLIND Analysis Method

Cut 1 *vs* Cut 2



Blind Near-Signal Region:
Test Predictions

If Cuts 1 and 2 are uncorrelated:

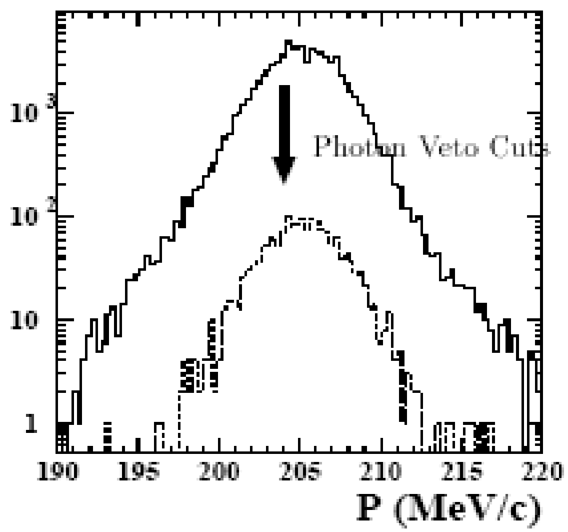
A/B=C/D

Background in A:

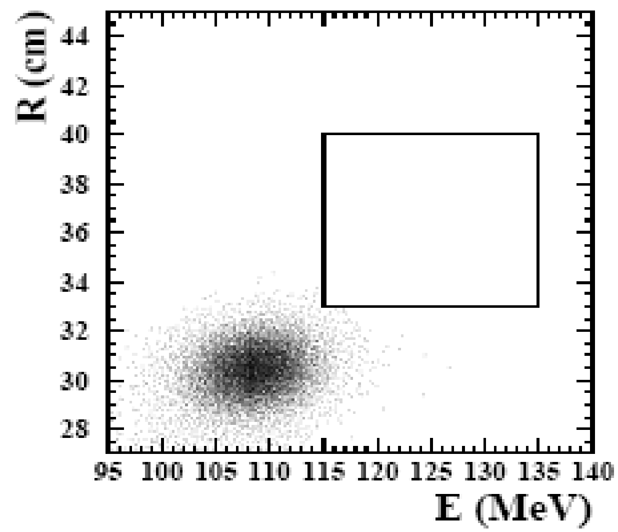
A=B C/D

Example: Estimating the $K_{\pi 2}$ Background from Data

Momentum with
Photon Veto Applied



Range vs. Energy with
Photon Veto Reversed



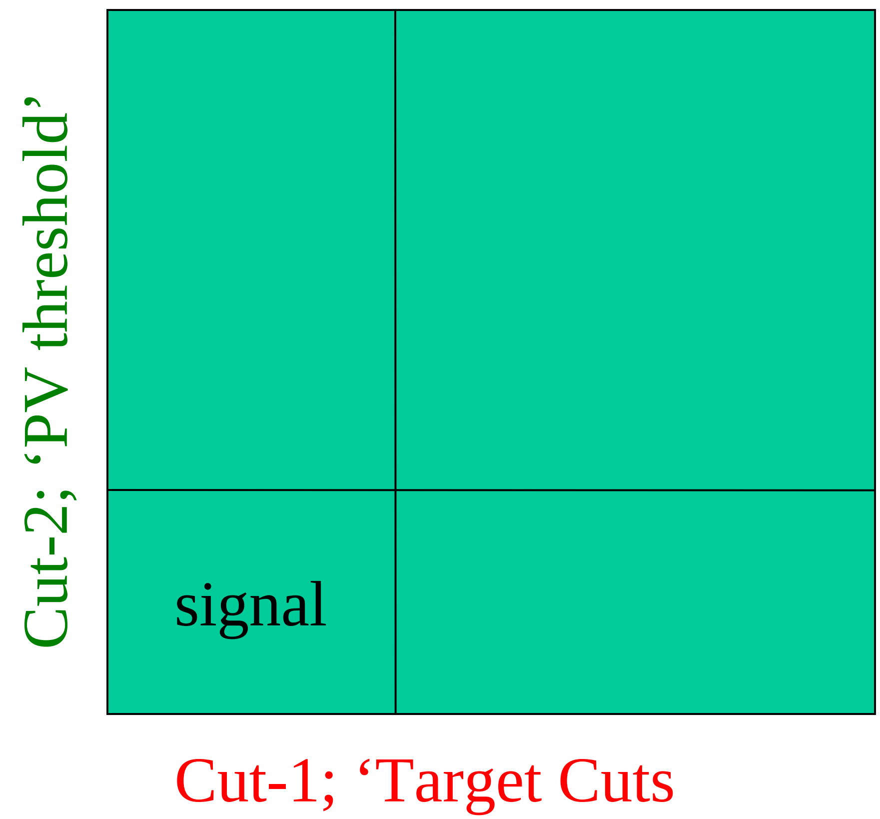
Left: Kinematically selected $K^+ \rightarrow \pi^+\pi^0$ with photon veto applied.
Photon veto: Typically 2-5 ns wide time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in momentum(P), range(R), energy(E)

Blind Analysis Strategy for PNN2

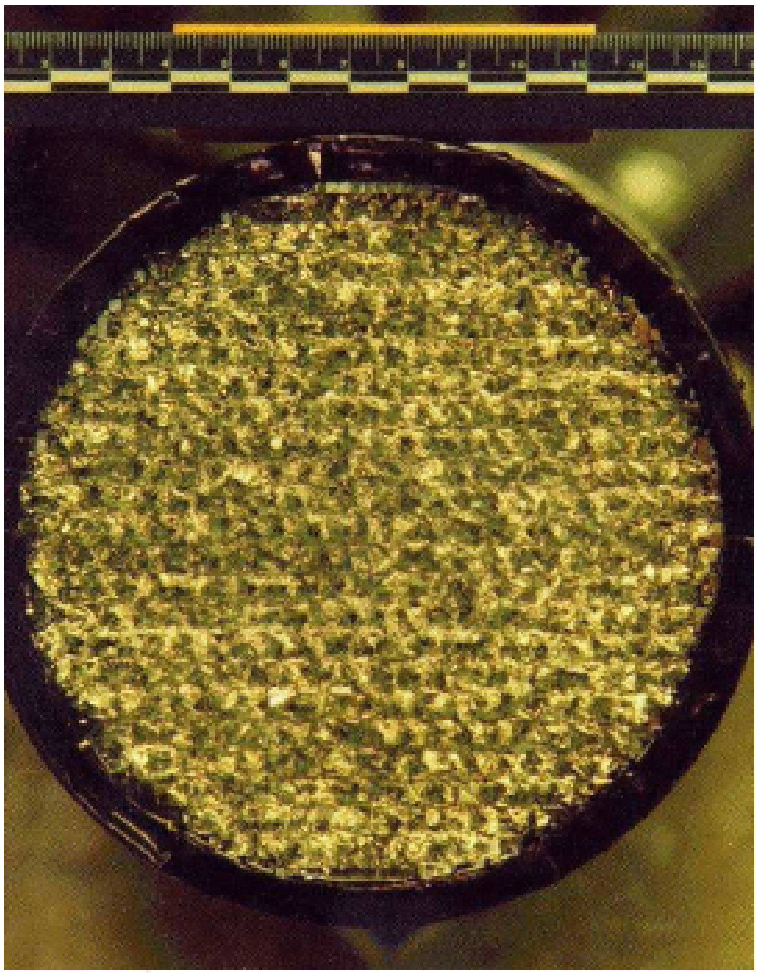
Mask the signal region.

- Develop the cuts and estimate the background (1/3 data); use data as much as possible in the background estimates.
- Bifurcated background analysis with (2/3) of data.
- Study correlations:
  Outside the box study
- Open the "box".

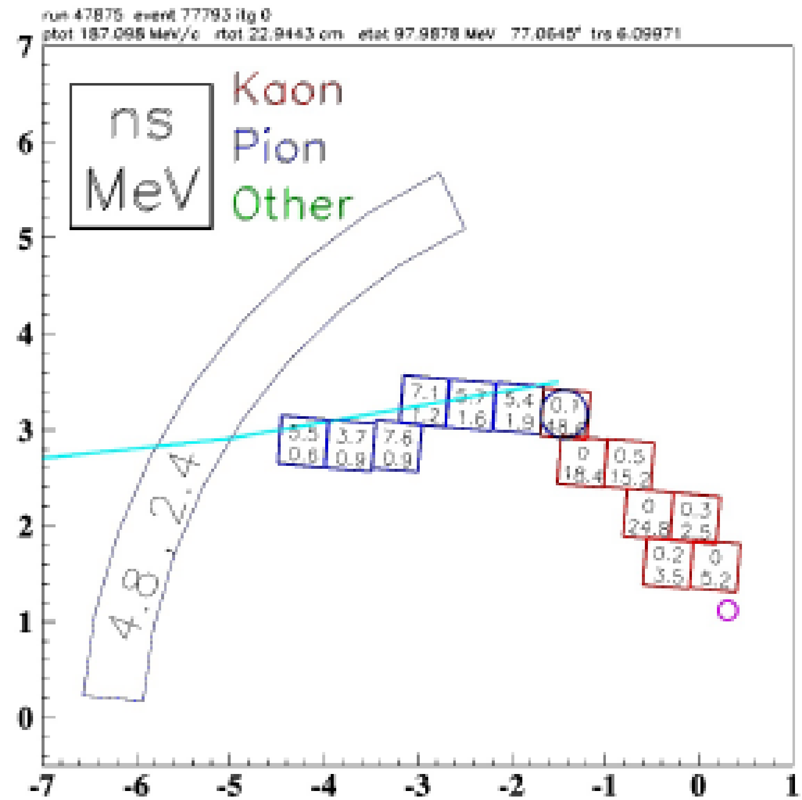


$K_{\pi 2}$: 1=Target scat. 2=Photon veto
K_{e4} : 1=T_π + Te 2=MC
$K_{\mu 2}$: 1=Kinematics 2=$\pi \rightarrow \mu \rightarrow e$

E949 scintillating fiber target

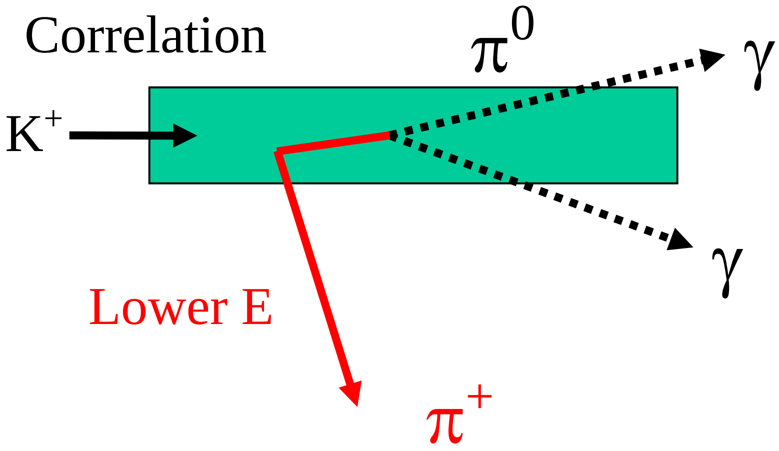


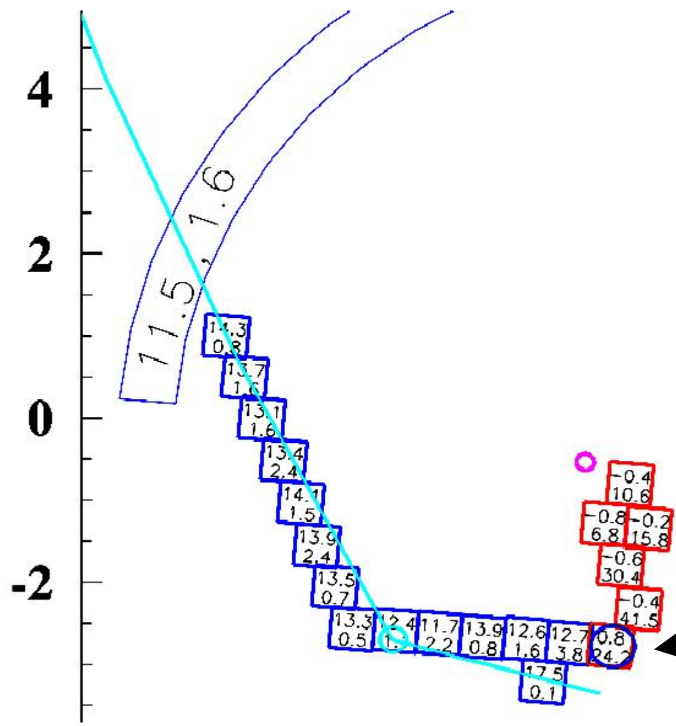
Each fiber is $0.5 \times 0.5 \times 300.0$ cm



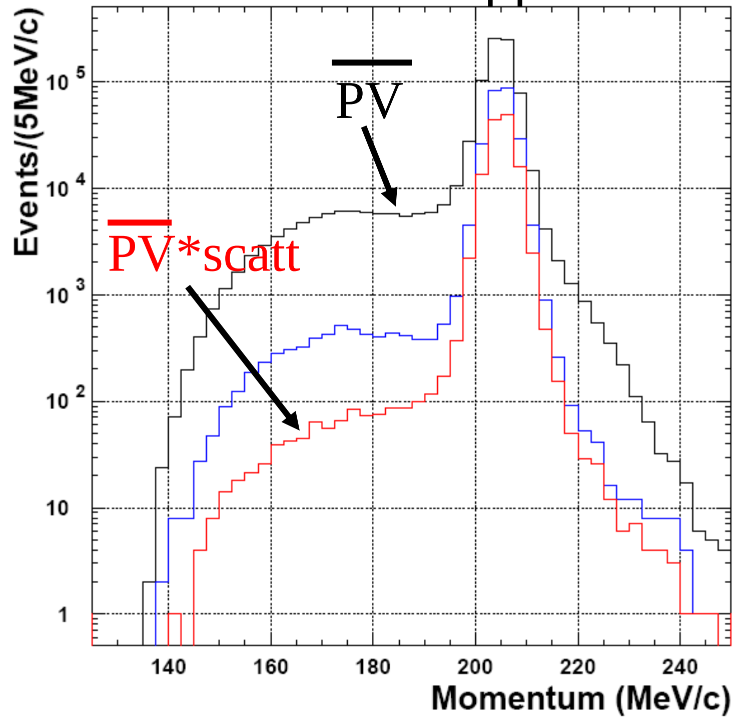
'Typical' pattern in target fibers for $K^+ \to \pi^+\pi^0$ decay.

$K^+ \rightarrow \pi^+ \pi^0$ Background from Scattering

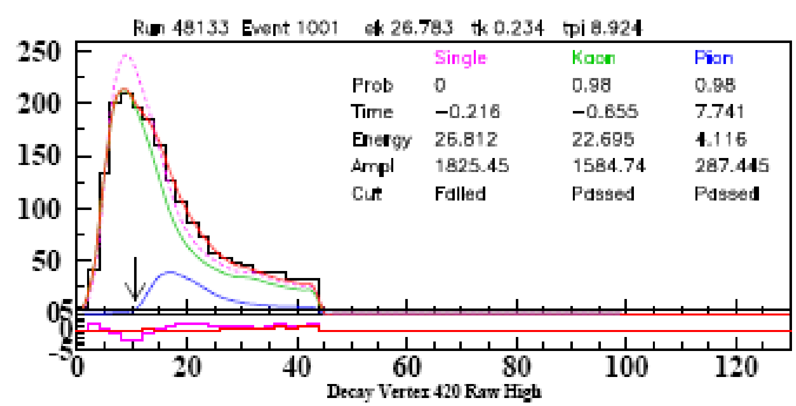




Scatter Cuts Suppression

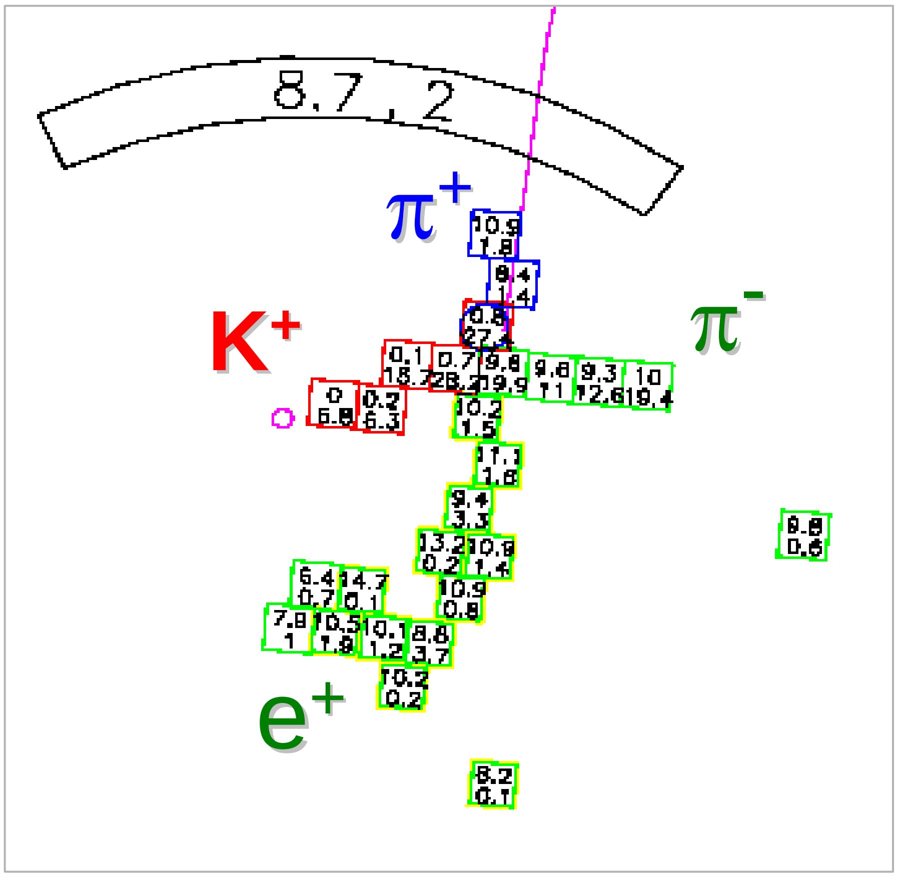


Excess Energy in Kaon Fiber

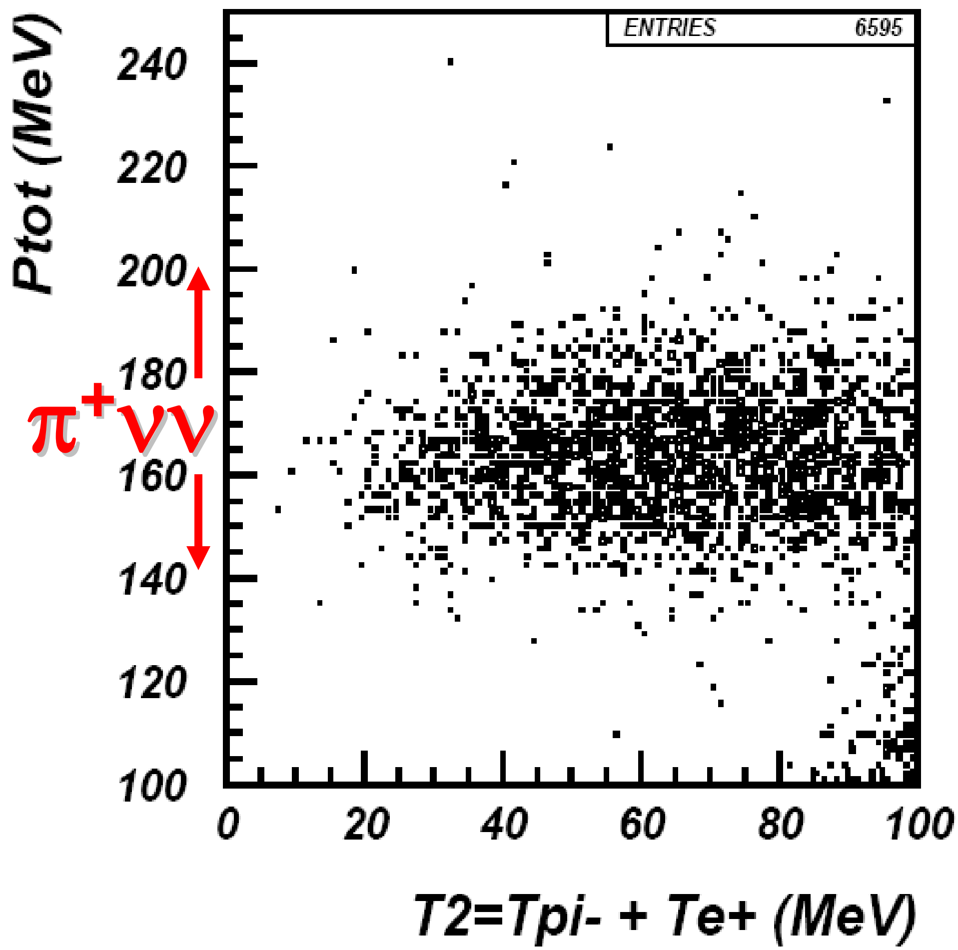


$K^+ \to \pi^+ \pi^- e^+ \nu$ (Ke4) Background

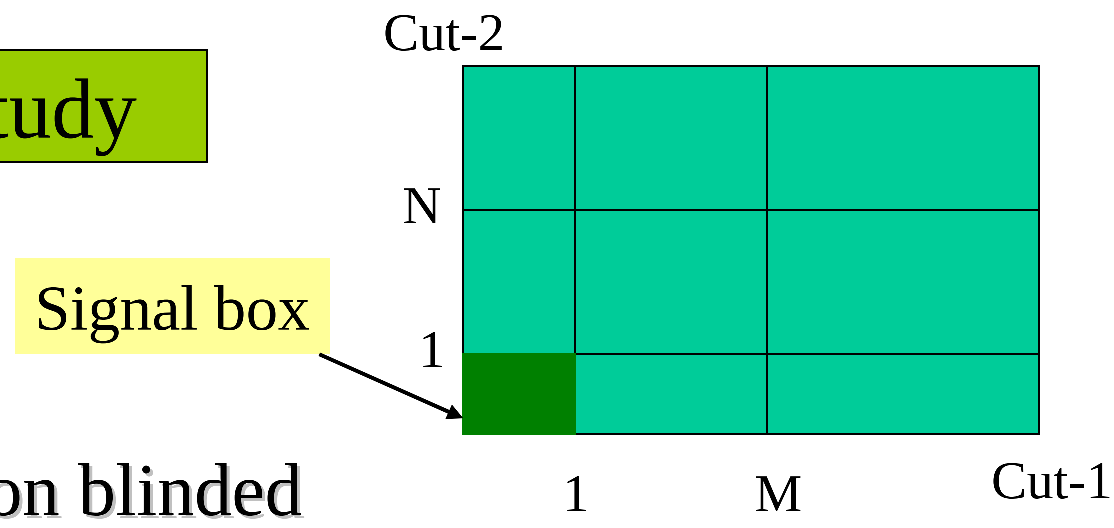
Ke4 candidate (data)



Ke4 MC Events



Correlation study



- Keep signal region blinded
- Relax photon veto or target pulse shape cut
- Compare predicted and observed events in the extended region.

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

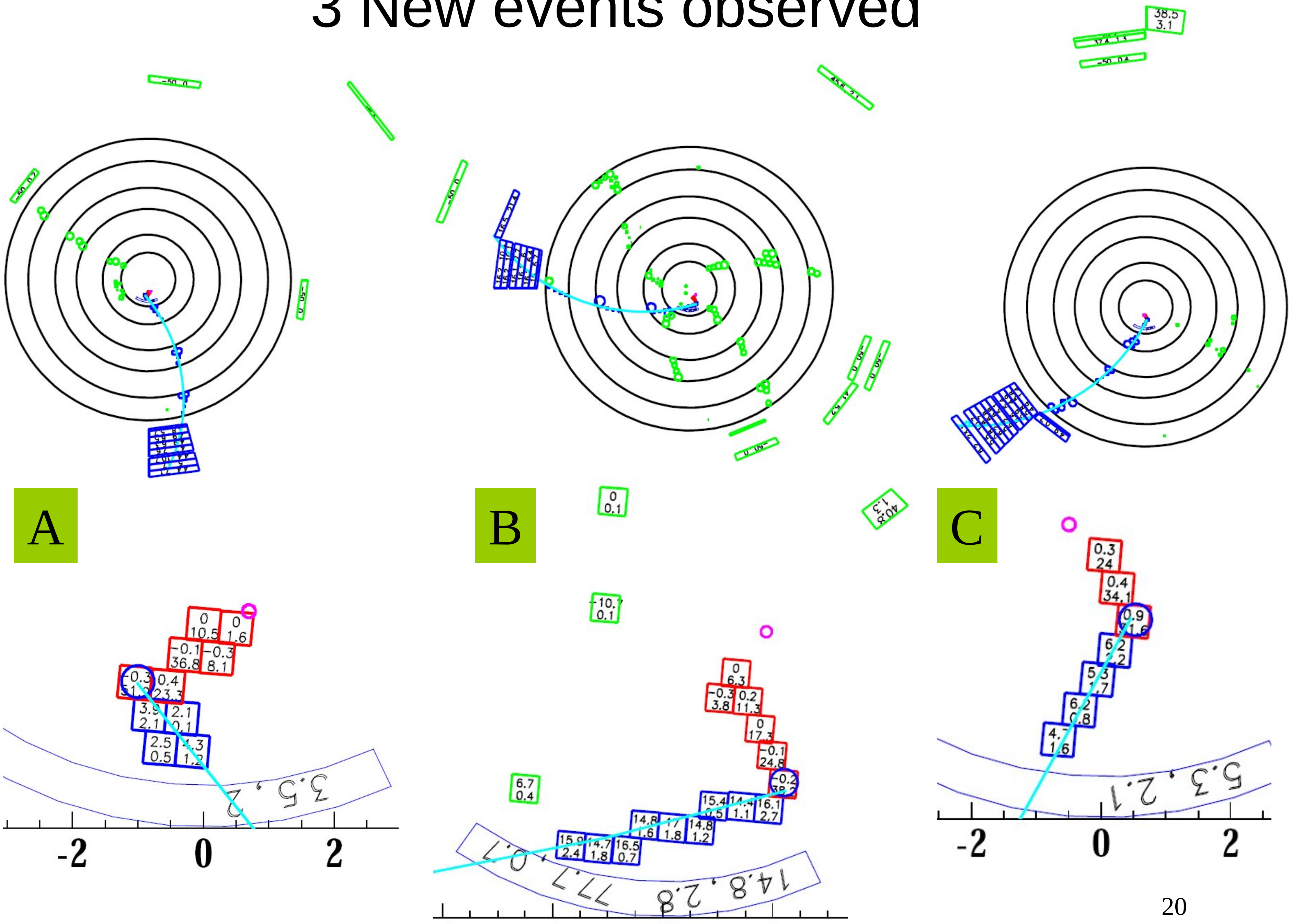
PNN2 Background summary

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

Sensitivity

	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}

3 New events observed

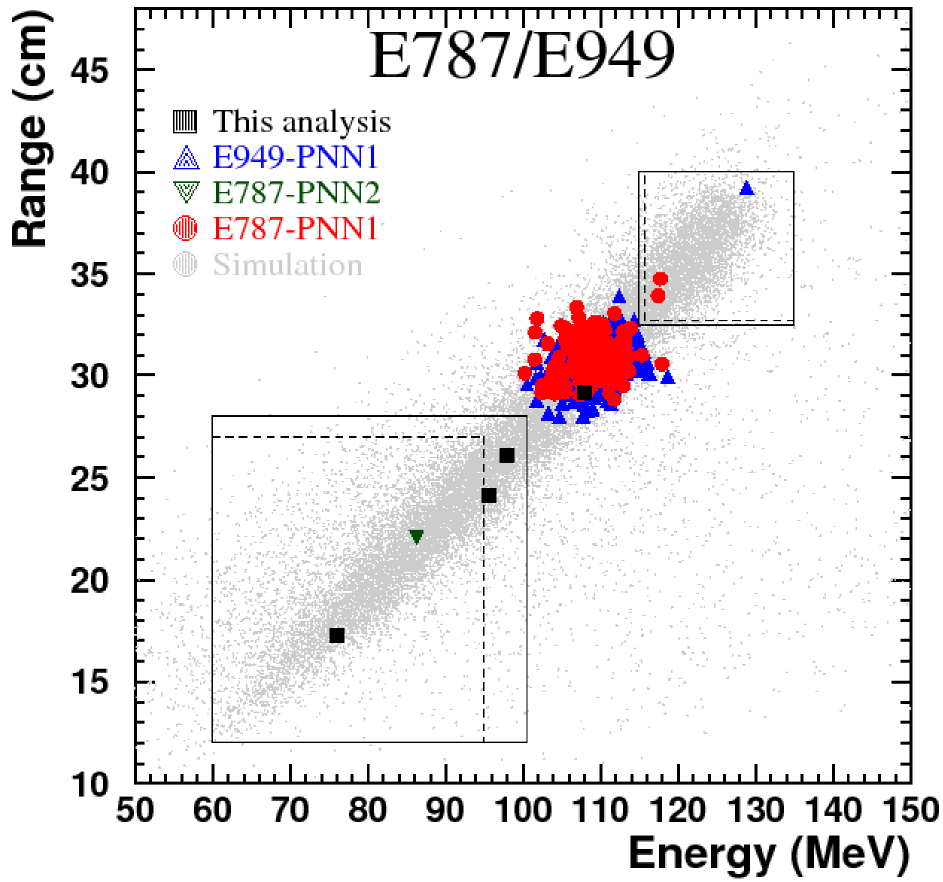


Division of the signal region

- The background is not uniformly distributed in the signal region.
- Use the remaining rejection power of photon veto, delayed coincidence, $\pi \to \mu \to e$ and kinematic cuts to divide the signal region into 9 cells with differing levels of signal acceptance (S_i) and background (B_i).
- Calculate $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ using S_i/B_i of any cells containing events using the likelihood ratio method.

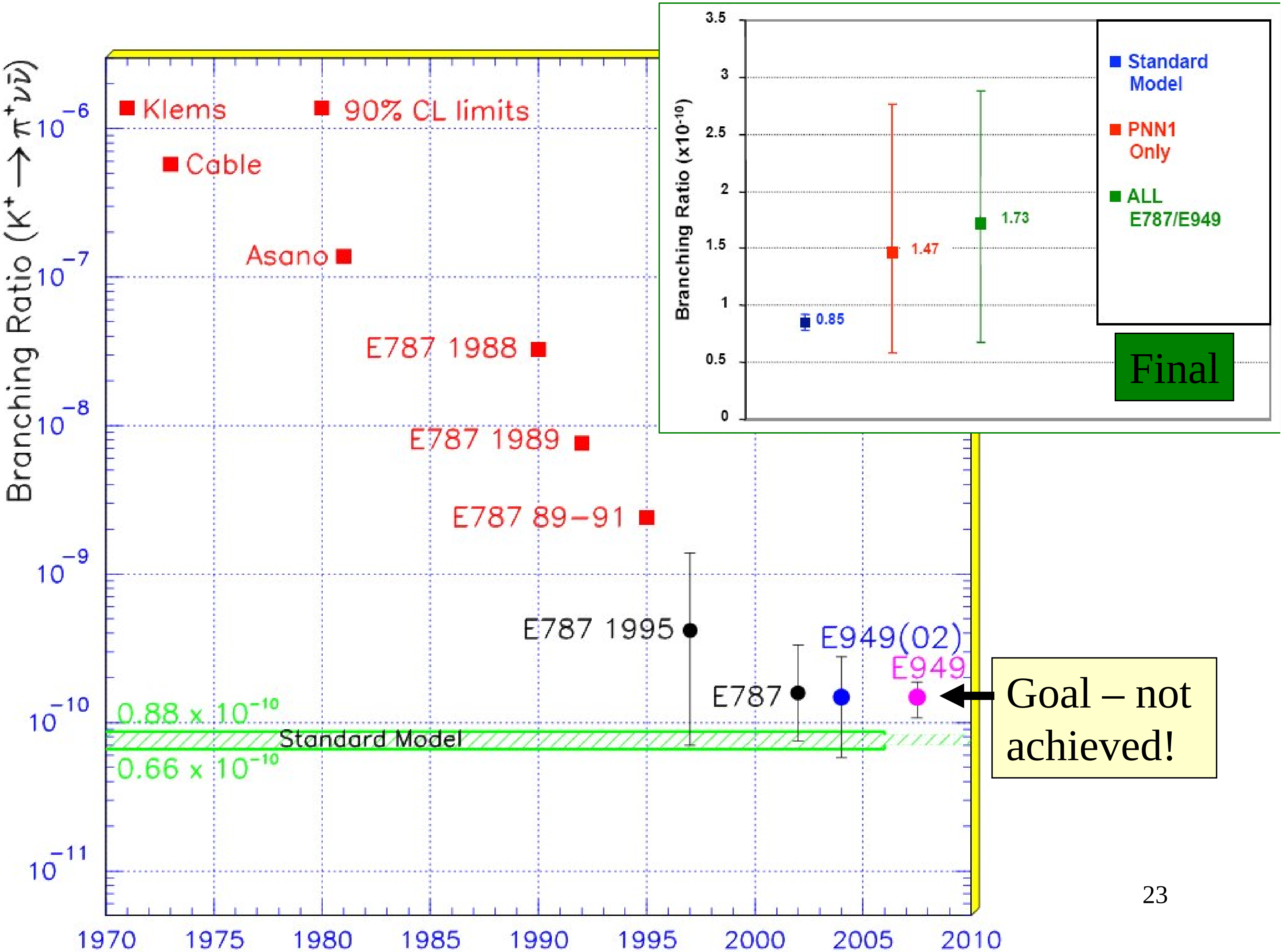
Final results from E787/E949

7 events observed



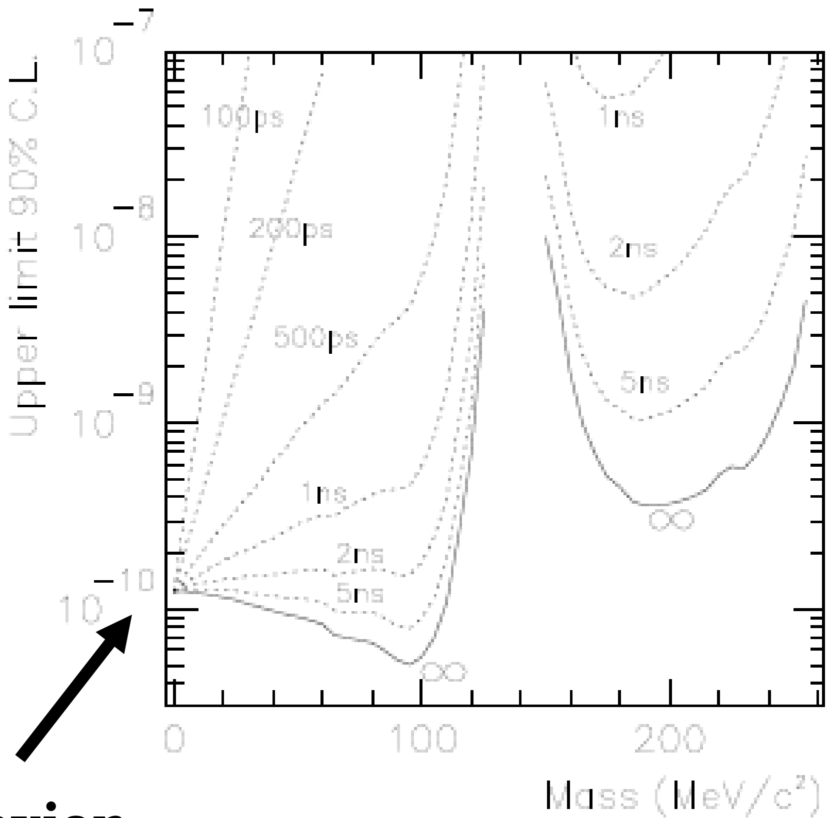
$$B(K^+ \to \pi^+ \nu \overline{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

Probability that All 7 events are due to background: 0.001



Goal – not achieved!

Search for $K^+ \to \pi^+ X$



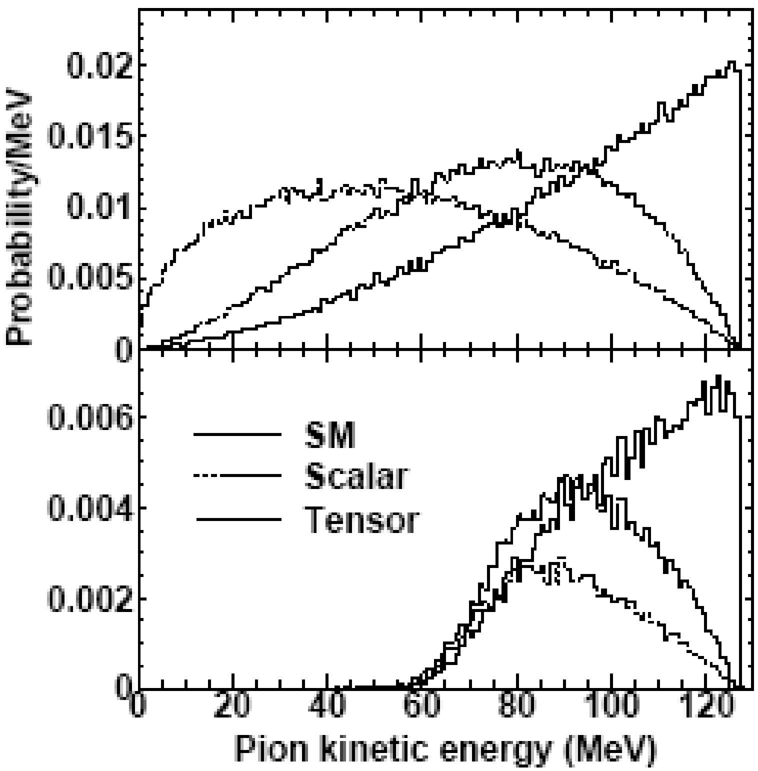
X=axion

90% CL limits on $K^+ \to \pi^+ X$ where X is a massive non-interacting particle for $\tau(X) \geq 100$ ps, assuming 100% detection efficiency if X decays within the outer radius of the barrel photon veto.

Also: $\mathcal{B}(K^+ \to \pi^+ X) < 5.6 \times 10^{-8}$ (90%CL) for $M(X) = M(\pi^0)$ from limit on $\mathcal{B}(\pi^0 \to \nu\bar{\nu}) < 2.7 \times 10^{-7}$ (E949, PRD**72** 091102 (2005)).

$$\mathcal{B}(K^+ \to \pi^+ X)\mathcal{B}(X \to \nu\bar{\nu}) < 3 \times 10^{-9}.$$

Search for $K^+ \to \pi^+ XX$



Interpretation assuming a scalar or tensor interaction:

$\mathcal{B}_{\rm scalar} = (9.9^{+8.5}_{-4.2}) \times 10^{-10}$

$\mathcal{B}_{\rm tensor} = (4.9^{+3.9}_{-2.4}) \times 10^{-10}$

Figure:

Top is simulated π^+ energy spectra

Bottom are events passing the trigger

BNL E787/E949 Results

Discoveries

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

$K^+ \to \pi^+ \gamma\gamma$

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

$K^+ \to \mu\nu\gamma(SD)$

$K^+ \to \pi^+ \pi^0 \gamma(DE)$

Searches

$K^+ \to \pi^+ a$

$K^+ \to \pi^+ \gamma$

$K^+ \to \pi^+ H$

$\pi^0 \to \nu\bar{\nu}$

$\pi^0 \to \gamma X$

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

$K^+ \to \pi^0 \pi^+ \nu\bar{\nu}$

Still to come: $K^+ \to \pi^0 \mu^+ \nu\gamma$, $K^+ \to \pi^+ \pi^0 \gamma, K^+ \to \mu\nu_H$

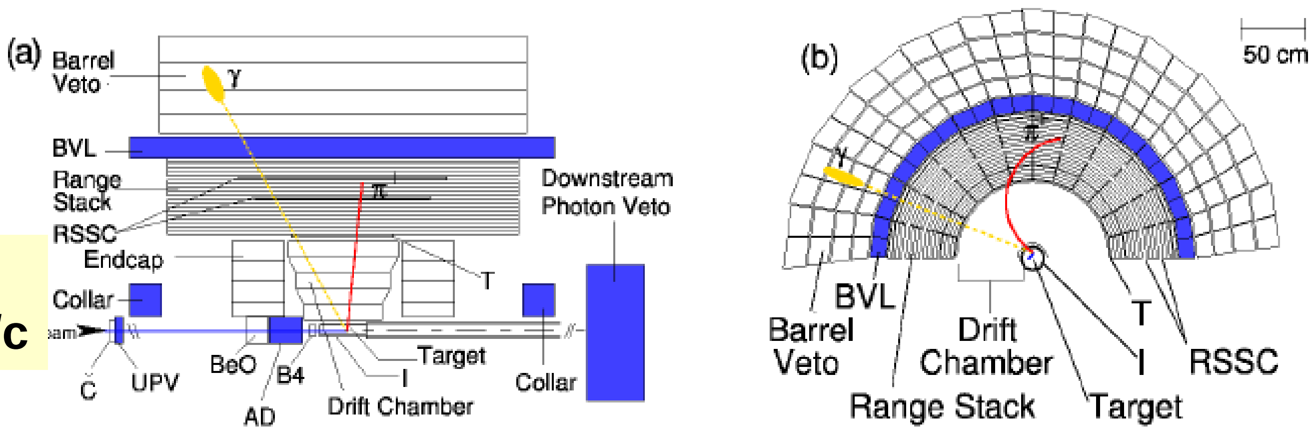
New opportunity:

$K^+ \to \pi^+ \nu \bar{\nu}$ at JPARC or Fermilab:

Stopped K technique: 1000 events!

100 x E949
Same technique.

Lower P_k
400 MeV/c



- Improved acceptance
- Higher stop efficiency at low momentum
- Reduced randoms and accidental spoiling of events (photon veto) due to low momentum.

Summary

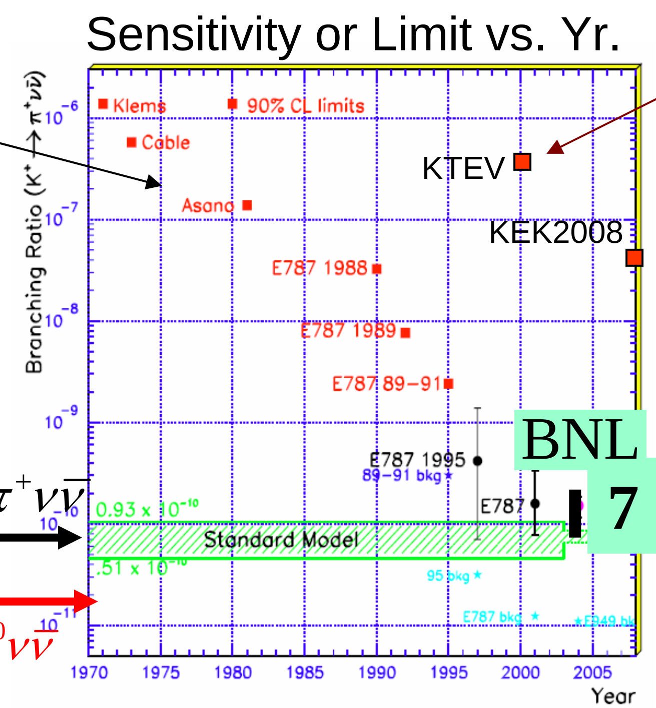
BNL E787/E949: $B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

$K \to \pi\nu\bar{\nu}$ experiments have come a long way

and the prospects are bright for future advancements.

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

$K_L^0 \to \pi^0 \nu\bar{\nu}$



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

SM

$K_L^0 \to \pi^0 \nu\bar{\nu}$

CERN NA62 $K^+ \to \pi^+ \nu\bar{\nu}$

J-PARC KOTO $K_L^0 \to \pi^0 \nu\bar{\nu}$

Fermilab, Project-X/J-PARC? 1000 events???