New results for $K^+ \to \pi^+ \nu\nu$ at low π^+ momentum from BNL E949

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New trends in high-energy physics (experiment, phenomenology, theory),
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Outline

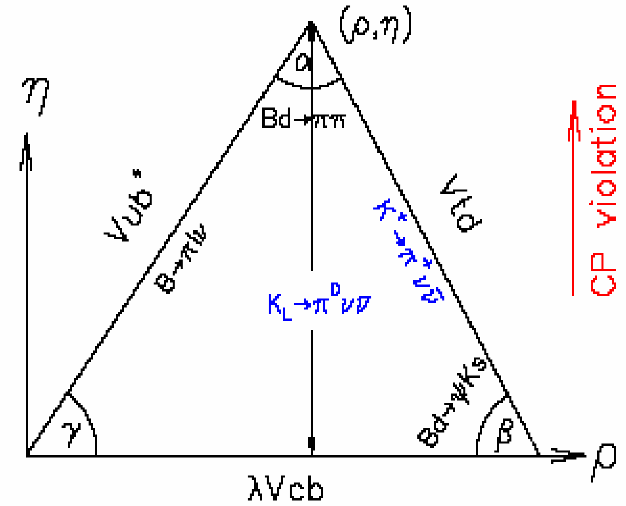
- Motivation
- Experiment E949
- Backgrounds: suppression and estimation
- Results
- Future

Motivation

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

Goal: Independently define the Unitarity triangle/ CKM matrix (A, λ, η, ρ Wolfenstein parameters)

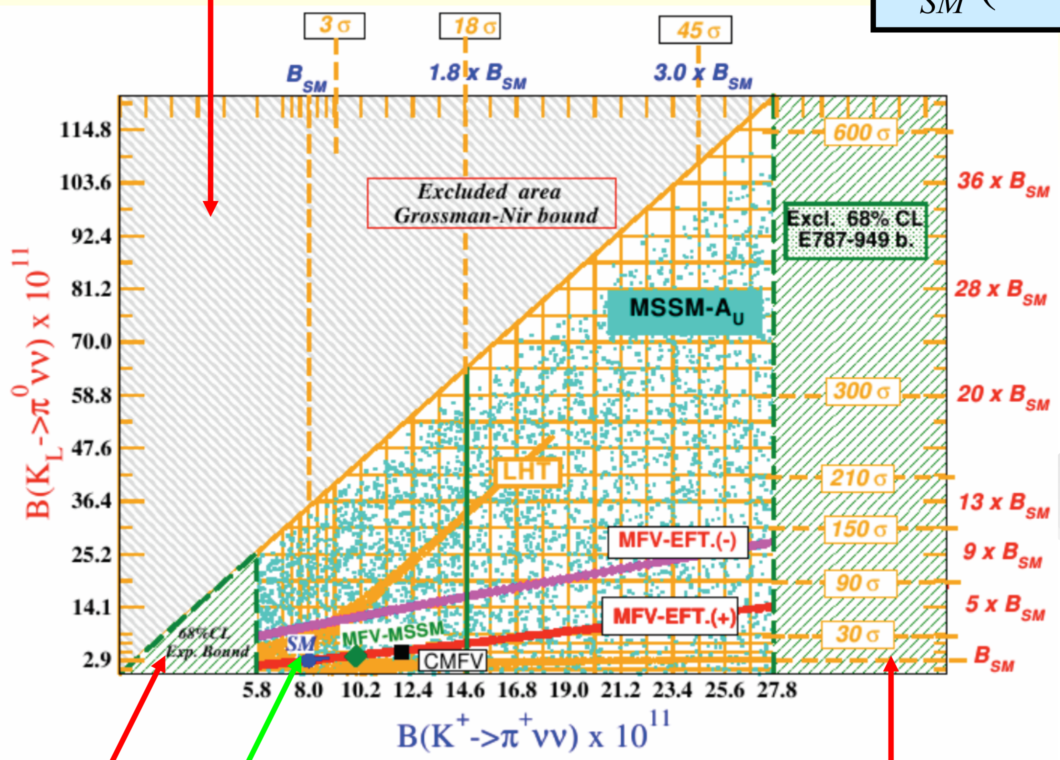
A better determination of V_{td} from $K^+ \to \pi^+ \nu\nu$ will provide a sensitive test of the SM by comparing the results from the K and B sector and probe new physics



Sensitive probe to new physics

$\mathcal{B}(K_L \to \pi^0 \nu\nu) \leq 4.4 \mathcal{B}(K^+ \to \pi^+ \nu\nu)$
Grossman – Nir Bound

$$\mathcal{B}_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$$



SM prediction

Excluded by E787/E949 results

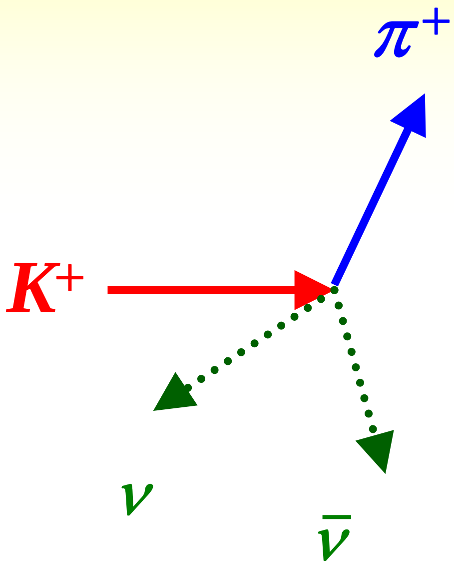
J. Brod and M. Gorbahn
arXiv:0805.4119

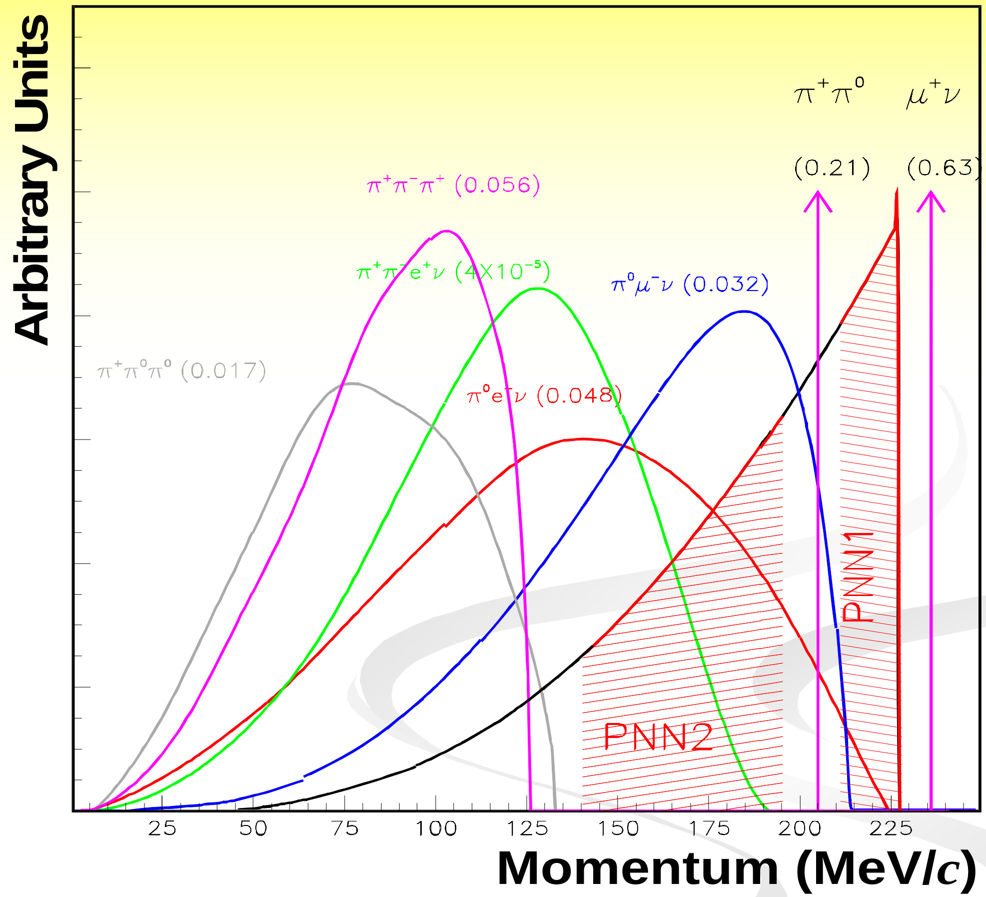
Because of the strong suppression of the *s*→*d* short-distance amplitude in the SM, rare *K* decays are the most sensitive probes of new physics.

Previous results

	PNN1	PNN2
$P(\pi^+)$(MeV/c)	[211,229]	[140,195]
Years	1995-98(E787) and 2002(E949)	1996-97(E787)
Stopped K^+	7.7×10^{12}	1.7×10^{12}
Candidates	3	1
Background	0.45 ± 0.06	1.22 ± 0.24
BR($K^+\to\pi^+\nu\nu$)	$(1.47^{+1.30}_{-0.89})\times10^{-10}$ (68%CL)	$< 22\times10^{-10}$ (90%CL)

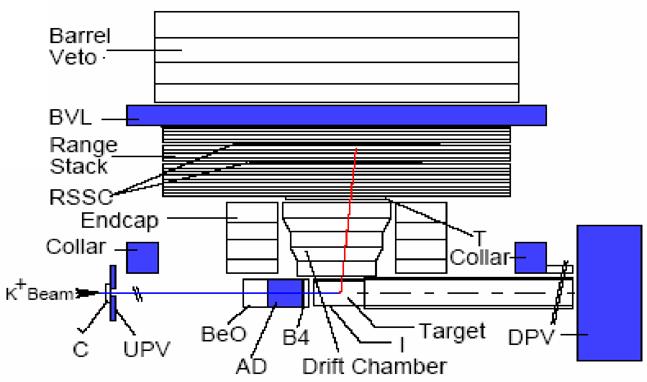
The experimental signature of $K^+ \to \pi^+ \nu\nu$ is single π^+ + "nothing"

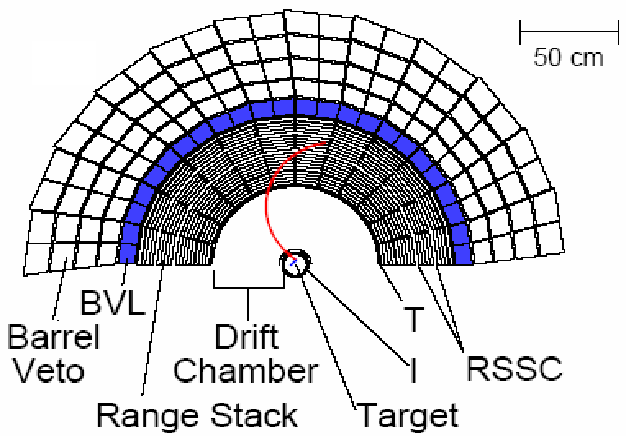




Momentum spectra of charged particles from K^+ decays in the rest frame

E949 Detector



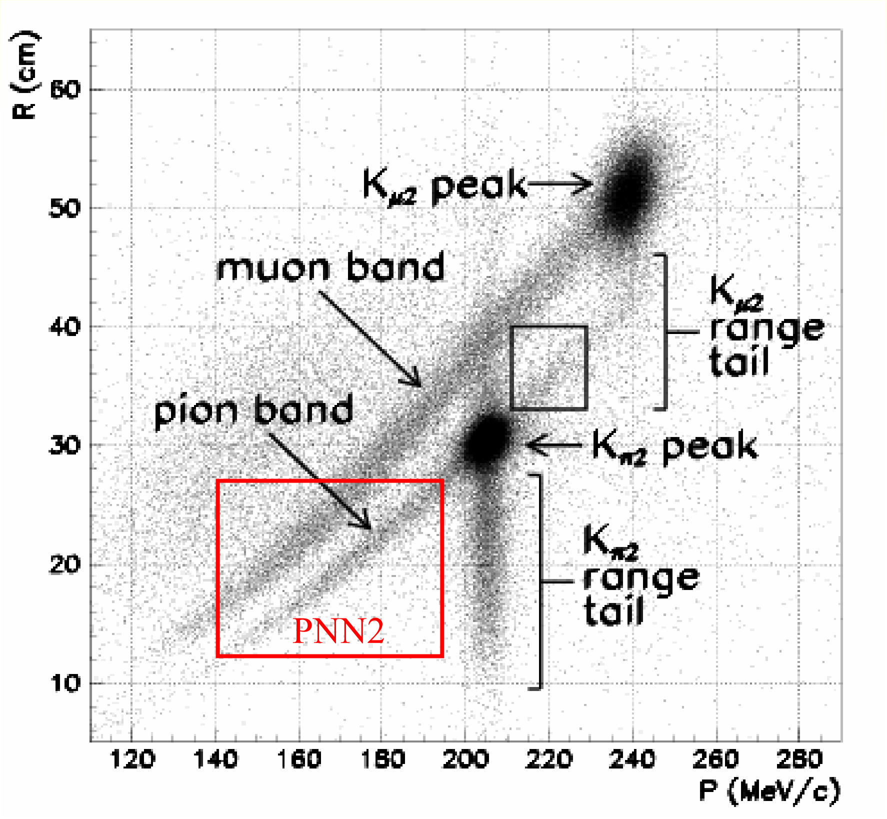


- Incoming ~700 MeV/c beam K slowed down by BeO and AD
- K^+ stops and decays at rest in scintillating fiber target – measure delay (at least 2 ns)
- Outgoing π^+ momentum is measured in UTC, energy & range in RS and target
- π^+ stops & decays in RS – detect $\pi^+ \to \mu^+ \to e^+$ chain
- Photons veto in BV – BVL, RS, EC, CO, USPV, DSPV

E949 analysis strategy

- *A priori* identification of background sources
- Use at least two uncorrelated cuts to estimate each background using information outside of the signal region
- Set cuts using 1/3 of data then measure backgrounds with remaining 2/3 sample
- Verify backgrounds estimate by loosening cuts and comparing observed and predicted rates
- "Blind" analysis: DON'T examine signal region until all backgrounds verified

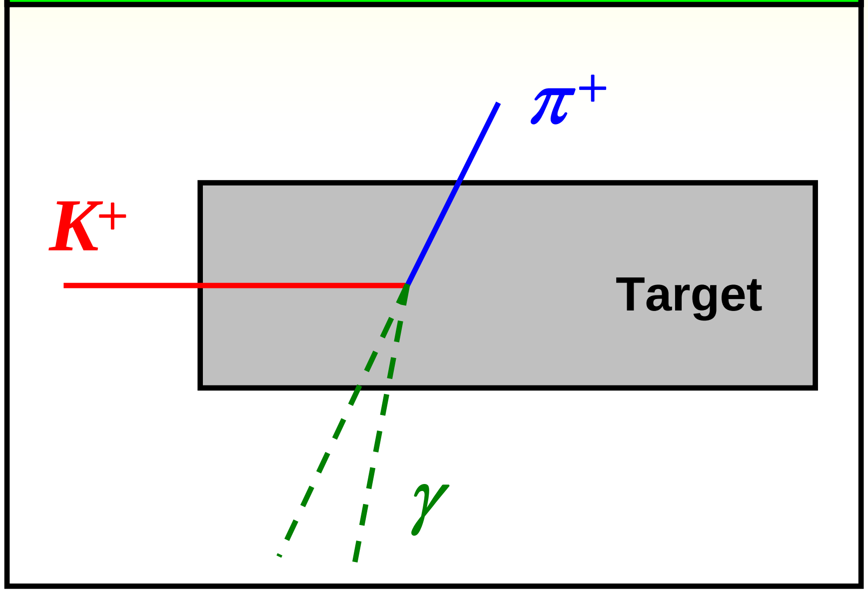
Backgrounds



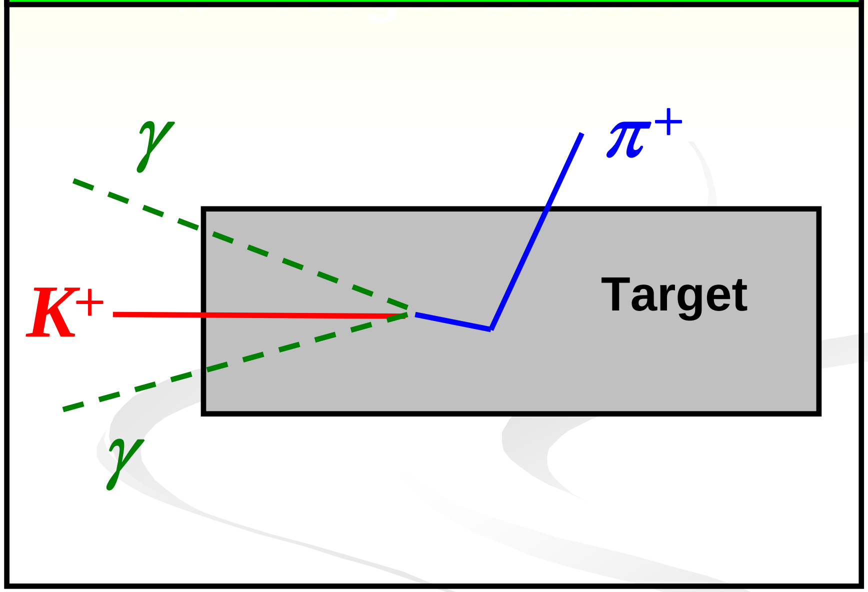
Background	BR ($\cdot\times10^{-3}$)
$K^+\to\pi^+\pi^o$ ($K_{\pi2}$)	212
Beam particles	-
$K^+\to\pi^+\pi^-e^+\nu_e$ (K_{e4})	0.039
$K^+\to\pi^+\pi^o\gamma$ ($K_{\pi2\gamma}$)	0.275
$K^+\to\pi^o\mu^+\nu_\mu$ ($K_{\mu3}$)	31.8
$K^+\to\mu^+\nu_\mu\gamma$ ($K_{\mu\nu\gamma}$)	5.5
CEX ($K^+n\to K^op$, $K^o_L\to\pi^+\mu^-\nu_\mu$ or $K^o_L\to\pi^+e^-\nu_e$)	Prob=0.0015 0.135 0.194

Main background is $K^+ \rightarrow \pi^+ \pi^0$

Regular $\pi^+\pi^0$



π^+ Target Scatter

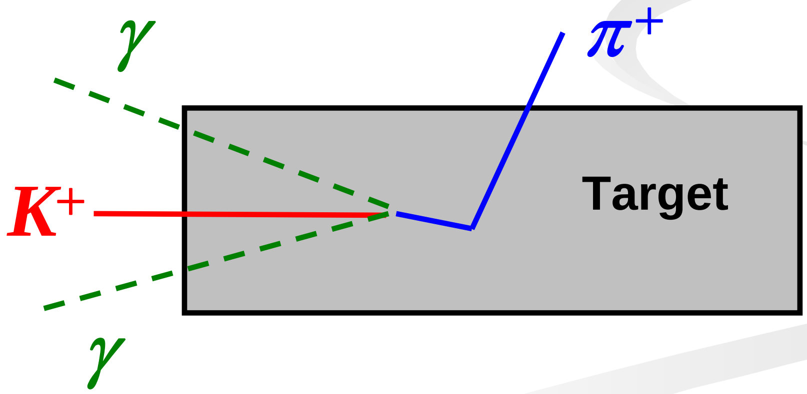


π^+ and π^0 are back to back so photons are directed to efficient part of the photon veto

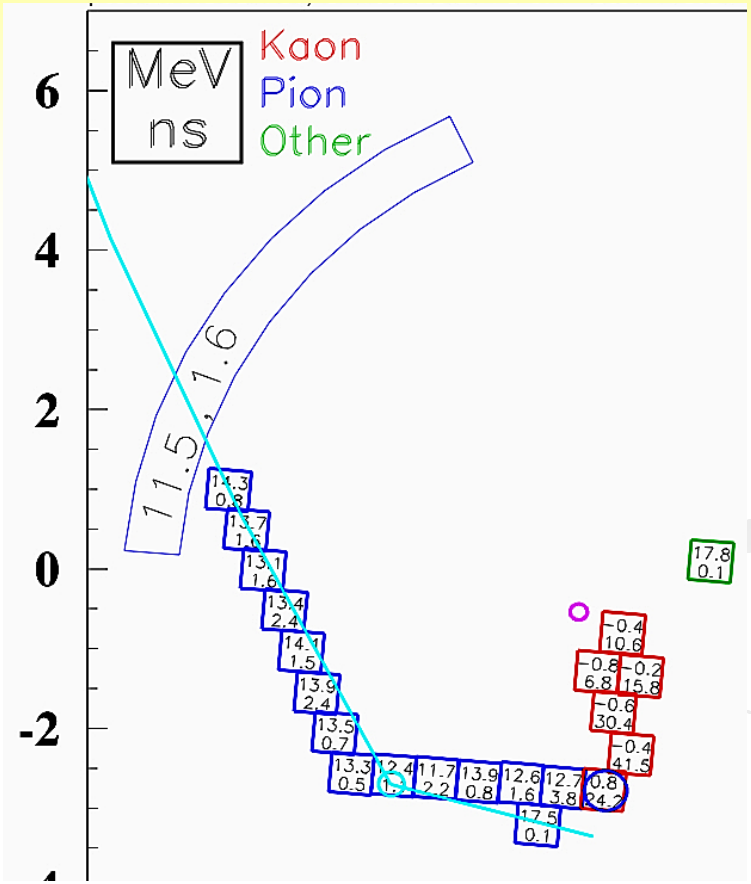
π^+ scatters in the target, loses energy and the photons lose directional correlation with the π^+

Suppression of $K_{\pi 2}$- scatter events

- Photon veto of $\pi^0 \rightarrow \gamma\gamma$. γ's may go to beam region => photon detection in this region is important
- Identification of π^+ scattering in the target:
  - kink in the pattern of the target fibers
  - π^+ track that doesn't point back to the K^+ decay point
  - energy deposits inconsistent with an outgoing π^+

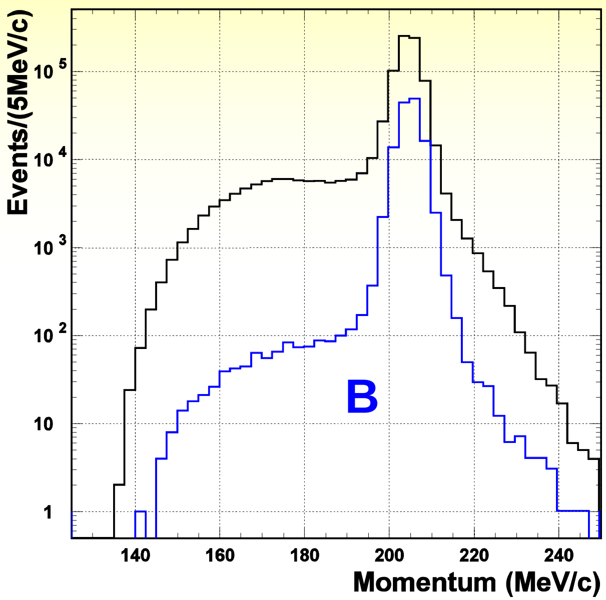


Identification of π^+ scattering

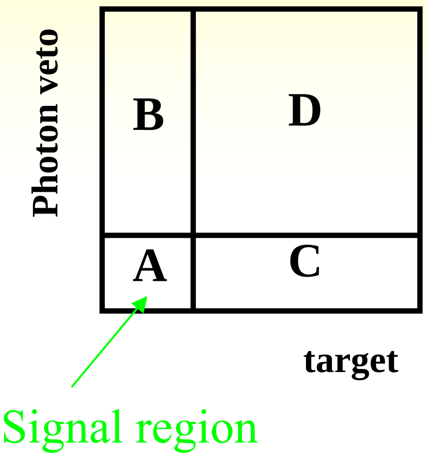


Kink in the pattern of target fibers

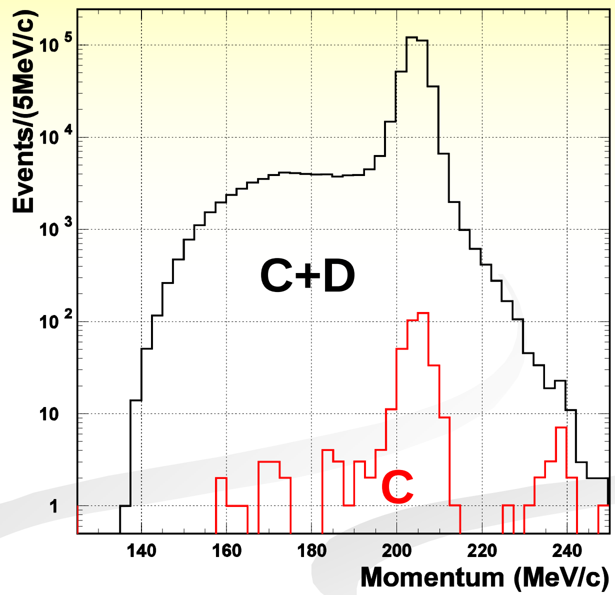
Two cuts used for suppression π^+-scatter events are photon veto and target-scatter cuts



photon veto is inverted,
target cuts are applied.



Background
A = BC/D

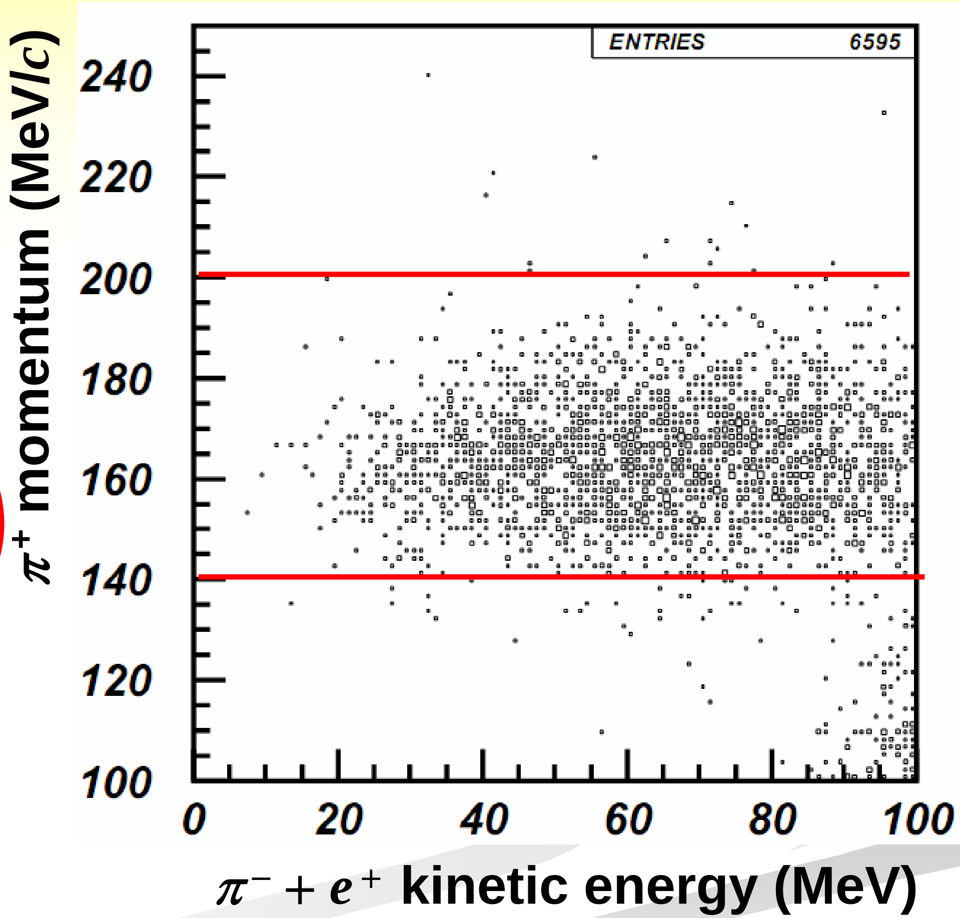


target cuts are inverted,
photon veto is applied.

Sample "B" also contains $K_{\pi 2}$-scatter in range stack and $K^+ \rightarrow \pi^+ \pi^0 \gamma$ events.

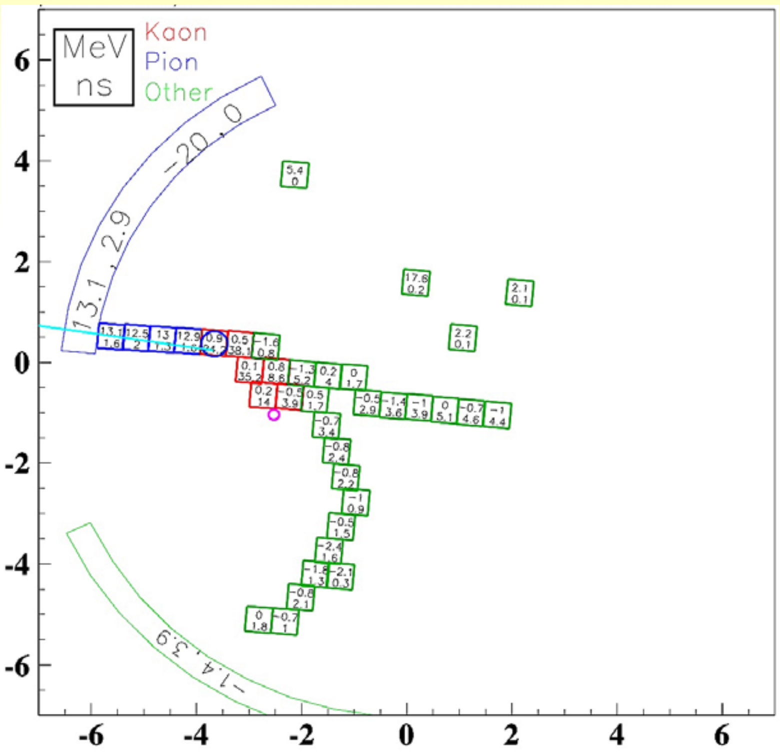
$K^+ \to \pi^+\pi^- e^+ \nu (K_{e4})$ background

- K_{e4} process forms a background when the π^- and e^+ interact in the target without leaving a detectable trace
- K_{e4} background could not be distinguished from the larger $K_{\pi 2}$-scatter background based solely on the π^+ track, and we cannot make a purely data-based background estimate

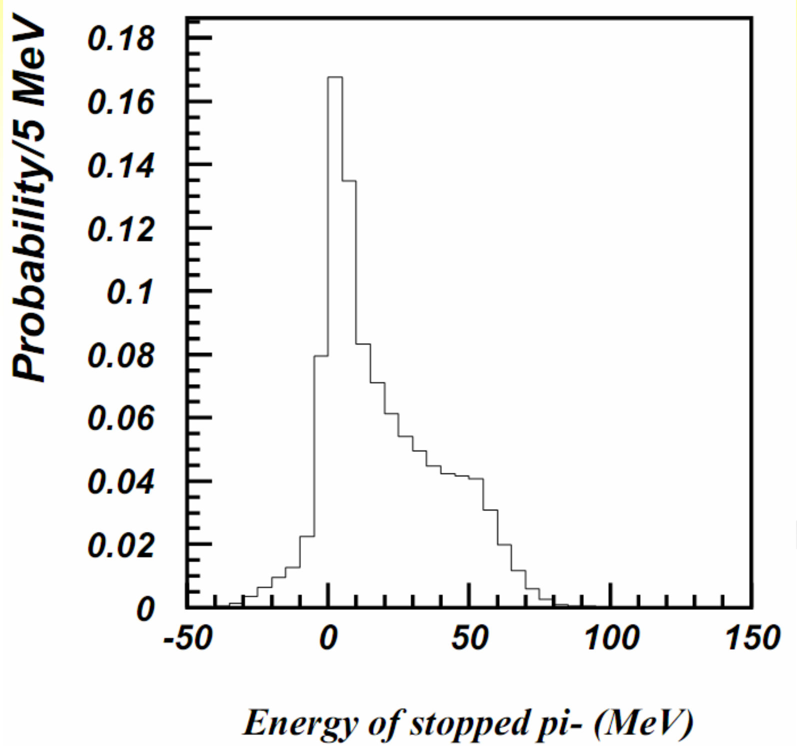


Use both data and Monte Carlo to estimate this background

$K^+ \rightarrow \pi^+ \pi^- e^+ \nu (K_{e4})$ background

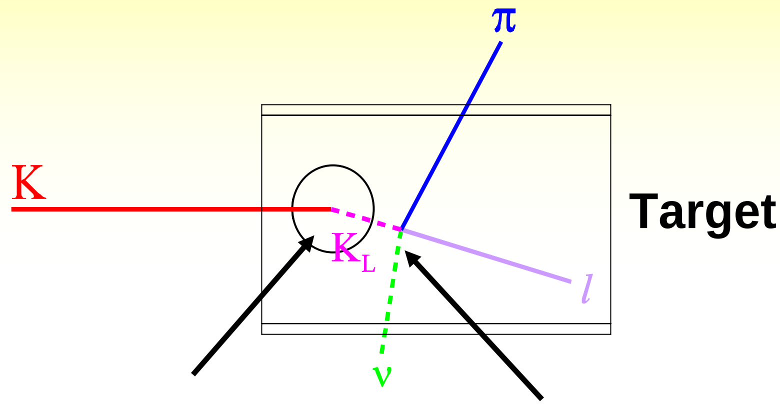


Use target pattern recognition to isolate K_{e4} sample



Estimate the rejection power of the target pattern recognition using simulated data supplemented by the measured π^- energy deposit in scintillator

Charge exchange (CEX) background



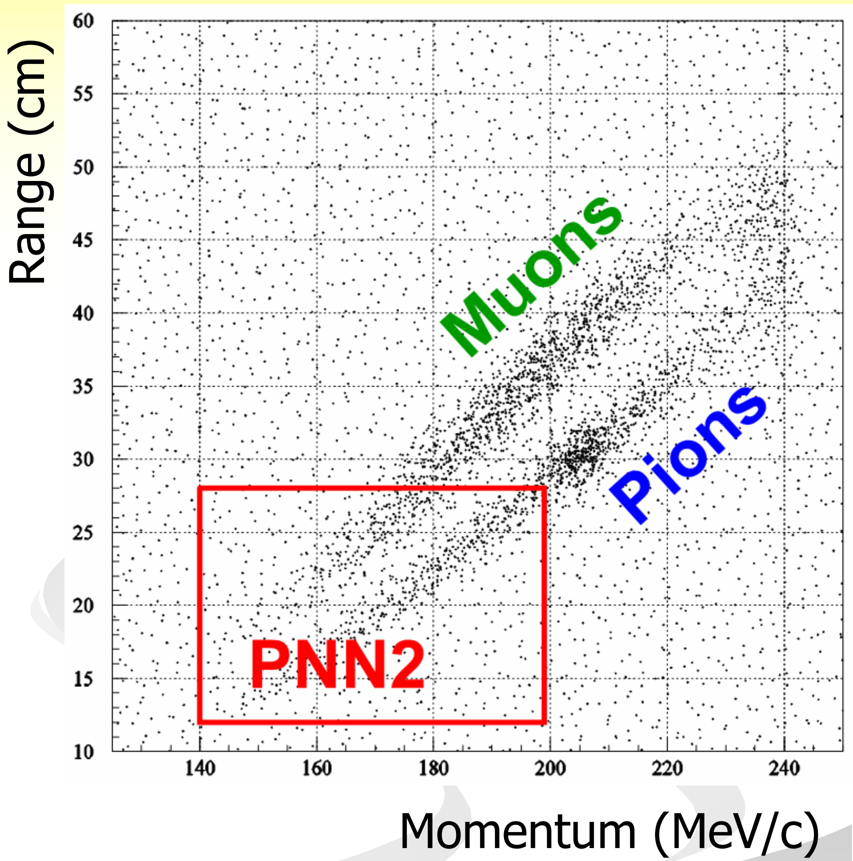
$$K^+ n \rightarrow K_L^0 p \qquad K_L^0 \rightarrow \pi^+ l^- \nu_l$$

This background is suppressed by K^+ decay time condition (K_s lifetime is only 0.1 ns) and target pattern recognition to identify gaps between K^+ and π^+ tracks. Additional suppression is provided by detecting the negative lepton.

Muon background

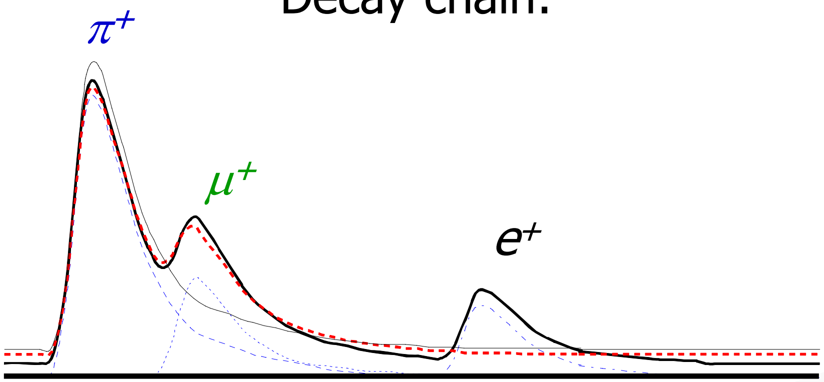
Due to kinematics constrain only multi-body decays $K^+ \to \mu^+ \pi^0 \nu_\mu$ and $K^+ \to \mu^+ \nu_\mu \gamma$ are important

This backgrounds are suppressed kinematically and by identification of π^+ decay



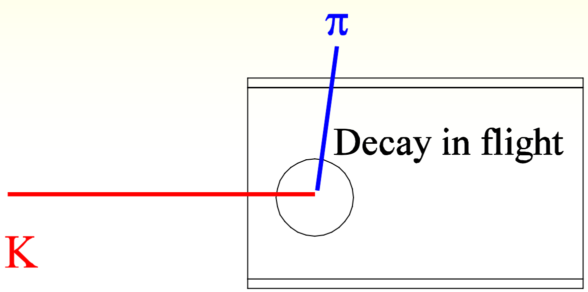
Muons have different kinematics parameters than pions

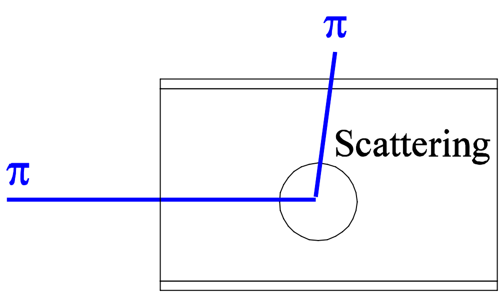
Decay chain:



Beam backgrounds

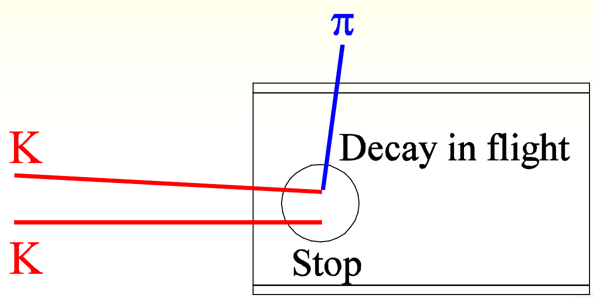
Single-beam

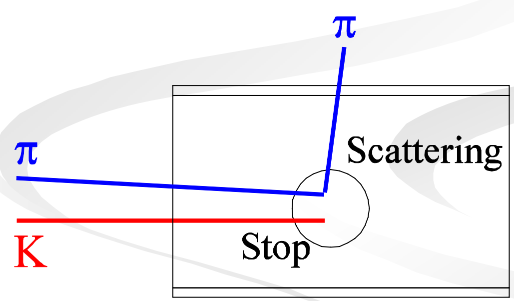




Suppressed by time delay

Double-beam





Suppressed by looking for any extra activities that are coincident with the charged track in the beam instrumentation

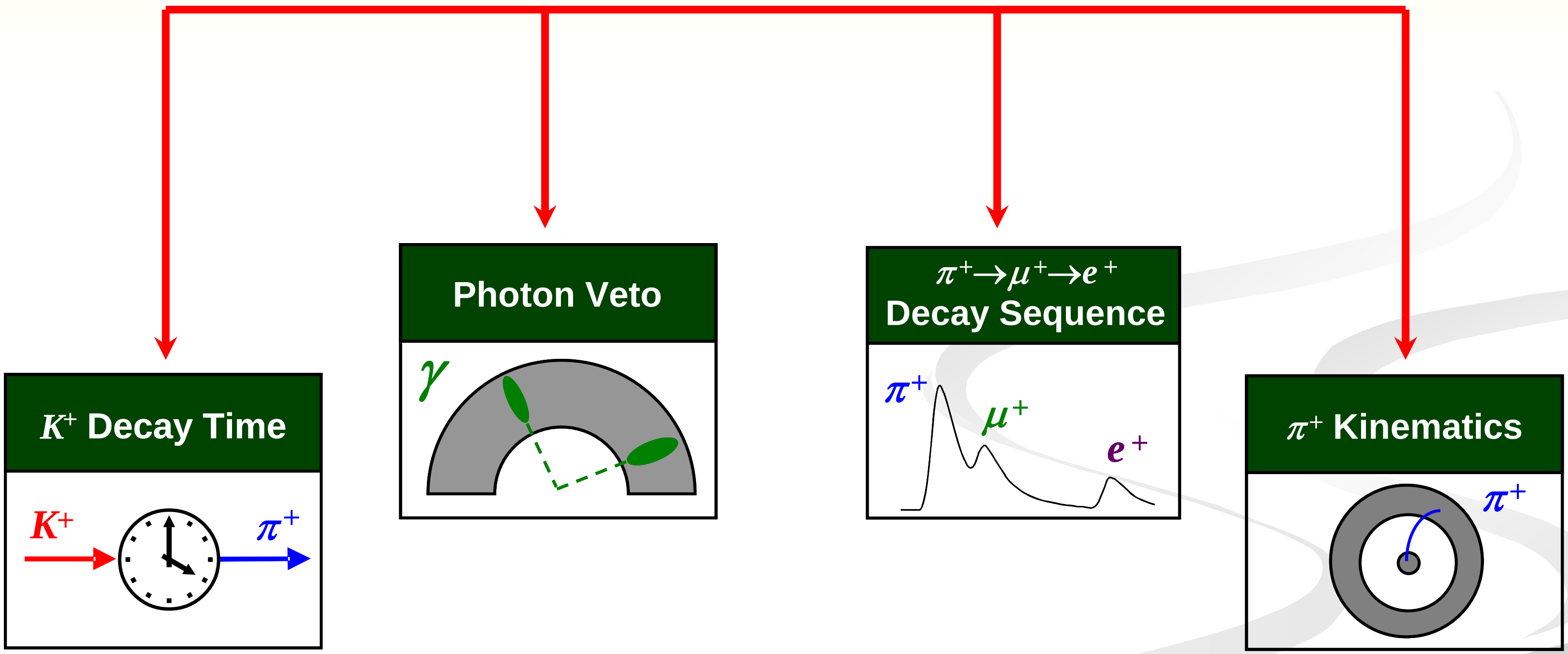
Total background in pnn2

Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	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

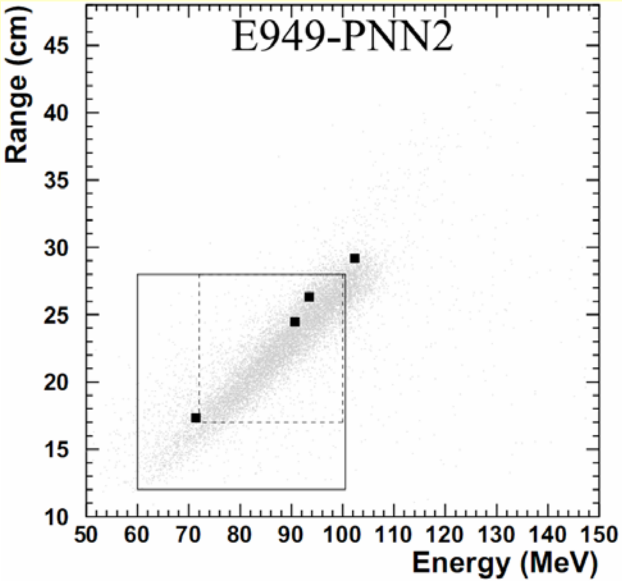
Compared to E787 pnn2 analysis, our total background was decreased by 24% and total acceptance was increased by 63%

Division of signal region

Use four cuts to divide the signal region into nine cells
with differing the relative signal-to-background levels



Examine the signal region



Solid line represents signal region, dashed shows tightened kinematics cuts. Gray points are simulated $K^+ \to \pi^+ \nu\nu$

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

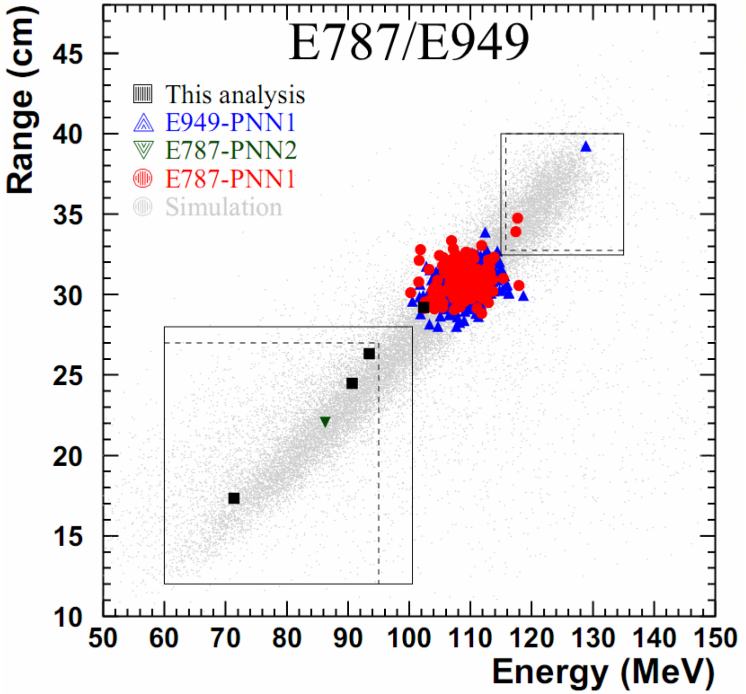
The probability of all 3 events to be due to background only is 3.7 %

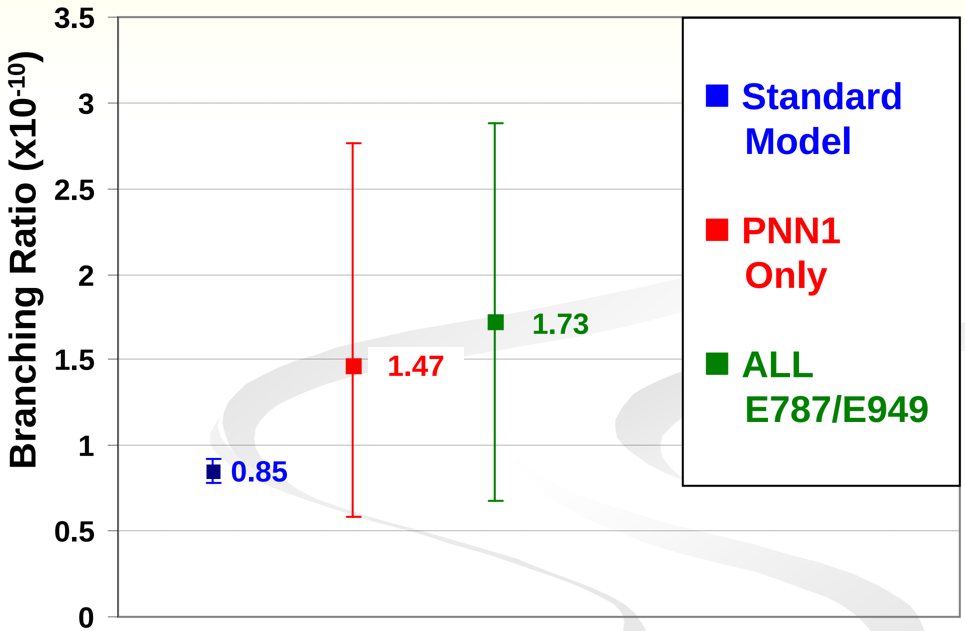
From these three new candidates alone

$$\mathcal{B}(K^+ \to \pi^+ \nu\nu) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$$

Combined E787/E949 results

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





The probability that all seven events were due to background only is 0.1%

Consistent with SM prediction

The future

- NA62 (formerly NA48/3) in preparation at CERN. The use of kaon decay-in-flight to measure $K^+ \to \pi^+ \nu\nu$ has not been attempted before.
- NA62 proposes to observe ≈ 65 $K^+ \to \pi^+ \nu\nu$ events
- There is a letter of intent for a stopped kaon decay experiment in Japan.
- Analyses of E949/E787 for other K^+ decay modes still continue.

Thank you! Questions?

Special thanks to David Jaffe and Joss Ives for the resources that made this talk possible