New results for $K^+ \rightarrow \pi^+ \nu \nu$ at low $\pi^+$ 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
Goal: Independently define the Unitarity triangle/CKM matrix \((A, \lambda, \eta, \rho\) 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.
Because of the strong suppression of the $s \to d$ short-distance amplitude in the SM, rare $K$ decays are the most sensitive probes of new physics.
## Previous results

<table>
<thead>
<tr>
<th></th>
<th>PNN1</th>
<th>PNN2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P(\pi^+)(\text{MeV/}c) )</td>
<td>([211,229])</td>
<td>([140,195])</td>
</tr>
<tr>
<td>Years</td>
<td>1995-98(E787) and 2002(E949)</td>
<td>1996-97(E787)</td>
</tr>
<tr>
<td>Stopped ( K^+ )</td>
<td>(7.7 \times 10^{12})</td>
<td>(1.7 \times 10^{12})</td>
</tr>
<tr>
<td>Candidates</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Background</td>
<td>(0.45 \pm 0.06)</td>
<td>(1.22 \pm 0.24)</td>
</tr>
<tr>
<td>( \text{BR}(K^+ \rightarrow \pi^+ \nu \nu) )</td>
<td>((1.47^{+1.30}_{-0.89}) \times 10^{-10}) (68%CL)</td>
<td>(&lt; 22 \times 10^{-10}) (90%CL)</td>
</tr>
</tbody>
</table>
The experimental signature of $K^+ \rightarrow \pi^+ \nu \nu$ is single $\pi^+$ + “nothing”
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 π⁺→μ⁺→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**

![Graph with data points and peaks]

<table>
<thead>
<tr>
<th>Background</th>
<th>BR ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(K_{\pi^2})$</td>
<td>212</td>
</tr>
<tr>
<td>Beam particles</td>
<td>-</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\nu_e(K_{e4})$</td>
<td>0.039</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\gamma(K_{\pi^2\gamma})$</td>
<td>0.275</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\mu^+\nu_\mu(K_{\mu^3})$</td>
<td>31.8</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu_\mu\gamma(K_{\mu\gamma})$</td>
<td>5.5</td>
</tr>
<tr>
<td>CEX ($K^+n \rightarrow K^0p$, $K^0_L \rightarrow \pi^+\mu^+\nu_\mu$ or $K^0_L \rightarrow \pi^+\nu_e$)</td>
<td>Prob=0.0015</td>
</tr>
<tr>
<td></td>
<td>0.135</td>
</tr>
<tr>
<td></td>
<td>0.194</td>
</tr>
</tbody>
</table>
Main background is $K^+ \rightarrow \pi^+ \pi^0$

Regular $\pi^+\pi^0$

$K^+$

Target

$\pi^+$

$\pi^0$

$\gamma$

$\gamma$

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

$\pi^+$ Target Scatter

$K^+$

Target

$\gamma$

$\gamma$

$\pi^+$ scatters in the target, loses energy and the photons lose directional correlation with the $\pi^+$
Suppression of $K_{\pi^2}$-scatter events

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

![Diagram of $K_{\pi^2}$-scatter events]
Identification of $\pi^+$ scattering

Kink in the pattern of target fibers
Two cuts used for suppression $\pi^+$-scatter events are photon veto and target-scatter cuts

 photon veto is inverted, target cuts are applied.

Sample “B” also contains $K_{\pi^2}$-scatter in range stack and $K^+\rightarrow\pi^+\pi^0\gamma$ events.
**$K^+ \rightarrow \pi^+ \pi^- e^+ \nu(K_{e4})$ background**

- $K_{e4}$ process forms a background when the $\pi$ and $e^+$ interact in the target without leaving a detectable trace.

- $K_{e4}$ background could not be distinguished from the larger $K_{\pi2}$-scatter background based solely on the $\pi^+$ track, and we cannot make a purely data-based background estimate.

Use both data and Monte Carlo to estimate this background.
\[ K^+ \rightarrow \pi^+ \pi^- e^+ \nu(K_{e4}) \text{ background} \]

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 \( \pi^- \) energy deposit in scintillator.
Charge exchange (CEX) background

\[ K^+ n \rightarrow K_L^0 p \quad K_L^0 \rightarrow \pi^+ l^- \nu_l \]

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 \( \pi^+ \) tracks. Additional suppression is provided by detecting the negative lepton.
Due to kinematics constrain only multi-body decays $K^+\rightarrow\mu^+\pi^0\nu_\mu$ and $K^+\rightarrow\mu^+\nu_\mu\gamma$ are important. This backgrounds are suppressed kinematically and by identification of $\pi^+$ decay.

Decay chain:

- $\pi^+
- \mu^+
- e^+$

Muons have different kinematics parameters than pions.
Beam backgrounds

Single-beam

K

π

Decay in flight

π

Scattering

Suppressed by time delay

Double-beam

K

π

Decay in flight

K

Stop

π

Scattering

π

Suppressed by looking for any extra activities that are coincident with the charged track in the beam instrumentation
Total background in pnn2

<table>
<thead>
<tr>
<th>Process</th>
<th>Bkgd events (E949)</th>
<th>Bkgd events (E787)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi2}$-scatter</td>
<td>$0.649 \pm 0.150^{+0.067}_{-0.100}$</td>
<td>$1.030 \pm 0.230$</td>
</tr>
<tr>
<td>$K_{\pi2\gamma}$</td>
<td>$0.076 \pm 0.007 \pm 0.006$</td>
<td>$0.033 \pm 0.004$</td>
</tr>
<tr>
<td>$K_{e4}$</td>
<td>$0.176 \pm 0.072^{+0.233}_{-0.124}$</td>
<td>$0.052 \pm 0.041$</td>
</tr>
<tr>
<td>CEX</td>
<td>$0.013 \pm 0.013^{+0.010}_{-0.003}$</td>
<td>$0.024 \pm 0.017$</td>
</tr>
<tr>
<td>Muon</td>
<td>$0.011 \pm 0.011$</td>
<td>$0.016 \pm 0.011$</td>
</tr>
<tr>
<td>Beam</td>
<td>$0.001 \pm 0.001$</td>
<td>$0.066 \pm 0.045$</td>
</tr>
<tr>
<td>Total bkgd</td>
<td>$0.93 \pm 0.17^{+0.32}_{-0.24}$</td>
<td>$1.22 \pm 0.24$</td>
</tr>
</tbody>
</table>

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

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

From these three new candidates alone

\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \nu) = (7.89^{+9.26}_{-5.10}) \times 10^{-10} \]
Combined E787/ E949 results

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

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 $K^+ \rightarrow \pi^+ \nu\nu$ has not been attempted before.
- NA62 proposes to observe $\approx 65 \ K^+ \rightarrow \pi^+ \nu\nu$ 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.