First results from BNL E949 on $K^+ \rightarrow \bar{\psi} + \bar{\psi}$

For the E949 collaboration:

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Stony Brook Physics Department HEP seminar
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Outline

• Theoretical motivation
  • CKM matrix
  • The decay $K^+ \rightarrow \pi^+ \pi^+$
• The E949 experiment:
  • Apparatus & measurement
  • Past (E787) results
  • Analysis strategy
• The result
The CKM matrix relates weak with strong eigenstates. In the Wolfenstein parametrization (to O(ε^7)),

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1
\end{pmatrix}
\]

where \( \bar{\rho} = \rho \left(1 - \frac{\lambda^2}{2}\right) \), \( \bar{\eta} = \eta \left(1 - \frac{\lambda^2}{2}\right) \)

**CP violation** arises from the irreducible imaginary phase of \( V_{\text{CKM}} \), because it’s 3x3 (3 generations)
$V_{\text{CKM}}$ is unitary, i.e. $VV^+=I \Rightarrow 6$ relations of $V_{ij} = 0$

For example, $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

$\Rightarrow$ A “Unitarity triangle” in the $\bar{\eta}$-\(\varsigma\) plane ($V_{ud} \cong 1$, $V_{tb} = 1$):

Processes w/ small theoretical uncertainties:

First E949 results
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A better determination of $V_{td}$ from $K^+ \to \delta^+ \bar{\tau}$ will provide a sensitive test of the SM by comparing the results from the K and B sector and probe new physics.
The SM $K^+ \rightarrow \bar{\phi}^+ \bar{\phi}^+ \bar{\phi}^+$ BR

- All processes at 2$^{nd}$ order
- Main contribution of $t$ in the loop ($u$ & $c$ cancel by GIM mechanism)
- Very theoretically "clean" calculation (precision $< 5\%$, uncertainties mainly from $c$ sector)

\[ BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) \propto \sum_{l=e,\mu,\tau} \left[ V^*_{cs} V_{cd} X(\chi_c) + V^*_{ls} V_{ld} X(\chi_t) \right] \times (HADR) \times (\nu\bar{\nu}) \]

... $BR \propto (\sigma \eta)^2 + (\rho_o - \bar{\rho})^2 \rightarrow$ ellipse in $\eta$-$\zeta$ plane

\[ \sigma = \left( \frac{1}{1 - \lambda^2 / 2} \right)^2 \]

\[ BR_{th}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10} \]
3-body decay w/ 2 missing particles: $0 \leq p_{\delta^+} \leq 227$ MeV/c \implies 
Signal: $\delta^+ + \text{nothing}$, backgrounds vetoed $\sim 10^{-11}$ !

- Need
  - particle identification (PID)
  - all other charged particles vetoed $< 10^{-3}$
  - redundant precise kinematic measurements

<table>
<thead>
<tr>
<th>Decay</th>
<th>$B$</th>
<th>PID</th>
<th>veto</th>
<th>kine.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$</td>
<td>0.21</td>
<td>-</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu$</td>
<td>0.63</td>
<td>√</td>
<td>-</td>
<td>√</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu\gamma$</td>
<td>0.005</td>
<td>√</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\mu^+\nu$</td>
<td>0.032</td>
<td>√</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0e^+\nu$</td>
<td>0.048</td>
<td>√</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-\pi^+$</td>
<td>0.056</td>
<td>-</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Decay product ($\delta^+$ or $\iota^+$) range in scintillator vs momentum:

- 2-body decay peaks
- 3-body decay bands
- Scattering tails
The E949 collaboration

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TRIUMF

Students and post-docs in red.

~70 physicists, plus a lot of hard work from earlier E787 collaborators.
The AGS extracts $\sim 65 \times 10^{12}$ protons at 22 GeV/c momentum over a 2.2 sec spill, every 5.4 sec.

They are shot on platinum target and particles produced $\sim 0^\circ$ are sent to the Low Energy Separated Beamline (LESB III), where $K^+$ are electrostatically separated from $\delta^+$ and focused.

Finally in the E949 target, $\sim 3.5 \times 10^6 K^+/spill$ arrive and stop, with a ratio of $K/\delta \sim 2.5-3$
• Incoming 700MeV/c beam K⁺: identified by ckov, WC, scint. hodoscope (B4). Slowed down by BeO and AD

• K⁺ stops & decays at rest in scintillating fiber target – measure delay (2ns)

• Outgoing δ⁺: verified by IC, VC, T counter. Momentum measured in UTC, energy & range in RS and target (1T magnetic field parallel to beam)

• δ⁺ stops & decays in RS – detect δ⁺→κ⁺→e⁺ chain

• Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV

The measurement w/ E949 detector

First E949 results
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The measurement w/ E949 detector

- Incoming 700MeV/c beam $K^+$: identified by ckov, WC, scint. hodoscope (B4). Slowed down by BeO and AD
- $K^+$ stops & decays at rest in scintillating fiber target – measure delay (2ns)
- Outgoing $\delta^+$: verified by IC, VC, T counter. Momentum measured in UTC, energy & range in RS and target (1T magnetic field parallel to beam)
- $\delta^+$ stops & decays in RS – detect $\delta^+ \rightarrow \bar{\nu}^+ \rightarrow e^+$ chain
- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV
- New/upgraded elements

First E949 results
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**Previous (E787) results (1)**

<table>
<thead>
<tr>
<th></th>
<th>PNN1</th>
<th>PNN2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$ (MeV/c)</td>
<td>[211,229]</td>
<td>[140,195]</td>
</tr>
<tr>
<td>Years</td>
<td>1995-98</td>
<td>1996-97</td>
</tr>
<tr>
<td>Stopped $K^+$</td>
<td>$5.9 \times 10^{12}$</td>
<td>$1.7 \times 10^{12}$</td>
</tr>
<tr>
<td>Candidates</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Background</td>
<td>$0.15 \pm 0.05$</td>
<td>$1.22 \pm 0.24$</td>
</tr>
<tr>
<td>$\text{BR}(K^+ \rightarrow \delta^{+}\bar{\nu})$</td>
<td>$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$</td>
<td>$&lt; 22 \times 10^{-10}$ (90% CL)</td>
</tr>
</tbody>
</table>

1995-97
1998
Monte Carlo
Previous (E787) results (2)

Candidate E787A

Candidate E787C

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What’s new in E949?

- New/upgraded PV elements
- More protons from AGS
- Improved tracking and energy resolution
- Higher rate capability due to DAQ, electronics and trigger improvements
- Lower beam duty factor (spill time/ time between spills)
- Lower proton energy
- Problematic separators, worse K/δ ratio
Photon Veto improvement

~ 2 × better rejection at nominal PNN1 acceptance (80%) or
~ 5% more acceptance with E787 rejection!

* Good news for PNN2 as well…

E787, E949
Analysis strategy (1)

- **“Blind” analysis**: don’t examine signal region (“the box”) until all bg are verified
- A priori identification of bg sources
- To avoid bias, tune cuts using *randomly selected* 1/3 of the data, then measure bg with remaining 2/3
- Suppress each bg source w/ at least two independent cuts
- Bg cannot be reliably simulated ⇒ measure w/ data by inverting cuts and measuring rejection

<table>
<thead>
<tr>
<th>Source</th>
<th>Suppression method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+\nu(\gamma) \ (K_{\mu2})$</td>
<td>Kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0 \ (K_{\pi2})$</td>
<td>√</td>
</tr>
<tr>
<td>Scattered $\pi^+$ beam</td>
<td>√</td>
</tr>
<tr>
<td>CEX</td>
<td></td>
</tr>
</tbody>
</table>

$\text{CEX} \equiv K^+n \rightarrow K^0p \ , \ K_L^0 \rightarrow \pi^+\ell^-\nu$
First E949 results
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Example: $K^+ \rightarrow \delta^+ \delta^i$ bg rejection

Select events with photons, measure rejection of kinematic cuts (P, R, E “box”)

Select $K^+ \rightarrow \delta^+ \delta^i$ kinematically, measure rejection of photon veto
Analysis strategy (2)

• Verify bg estimates & check for correlations by *simultaneously* loosening both cuts and comparing observed and predicted number of events remaining.

• Construct **background functions** by varying *one cut at a time*, keeping the other inverted. Use them to estimate bg in the box.

• Use MC to measure geometrical acceptance, verify by measuring $BR(K^+ \rightarrow \bar{\delta}^+\delta^i)$
**Expected bg**

<table>
<thead>
<tr>
<th></th>
<th>PV×KIN</th>
<th>Observed</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi_2}$</td>
<td>$10 \times 10$</td>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>$K_{\mu_2}$</td>
<td>$10 \times 10$</td>
<td>0</td>
<td>0.35</td>
</tr>
<tr>
<td>$K_{\mu m}$</td>
<td>$10 \times 10$</td>
<td>1</td>
<td>0.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>TD×KIN</th>
<th>Observed</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi_2}$</td>
<td>$10 \times 10$</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>$K_{\mu_2}$</td>
<td>$10 \times 10$</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>$K_{\mu m}$</td>
<td>$10 \times 10$</td>
<td>1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

$K_{\text{im}}$ :: 3-body decays w/ muons ($K^+\rightarrow i^+i\bar{a}$, $\hat{E}^+\rightarrow \delta^+\delta i$) and $\hat{E}^+\rightarrow \delta^+\delta i$, $\delta^+\rightarrow i^+i$

TD :: $\delta \rightarrow i \rightarrow e$ identification

PV :: Photon Veto

KIN :: kinematic cuts

M×N :: reduction in rejection w.r.t. predefined 1×1 region by loosening the cuts - *same increase in bg expected*

Quantify consistency: Fit $N_{\text{obs}} = cN_{\text{pred}}$ and expect $c = 1$.  

<table>
<thead>
<tr>
<th>Background</th>
<th>$c$</th>
<th>$\chi^2$</th>
<th>Probability</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi_2}$</td>
<td>$0.85^{+0.12}_{-0.11}$</td>
<td>0.17</td>
<td>0.216 ± 0.023</td>
<td></td>
</tr>
<tr>
<td>$K_{\mu_2}$</td>
<td>$1.15^{+0.25}_{-0.21}$</td>
<td>0.67</td>
<td>0.044 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>$K_{\mu m}$</td>
<td>$1.06^{+0.35}_{-0.29}$</td>
<td>0.40</td>
<td>0.024 ± 0.010</td>
<td></td>
</tr>
</tbody>
</table>

Total bg in signal region: $0.30 ± 0.03$

First E949 results

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**E949 improved analysis strategy**

- E787 bg estimation methods are reliable ⇒ confident to increase signal region by loosening cuts to gain acceptance, at cost of more total bg

- Divide signal region into cells, calculate expected bg ($b_i$) and signal ($s_i$) for each cell using the background functions

- Calculate BR using $s_i/b_i$ of cells where event(s) are found, using likelihood ratio method:

$$
\text{Maximize } X = \prod_{i=1}^{n} X_i, \quad X_i = \frac{d_i!}{e^{-b_i} b_i^{d_i} d_i! \left(s_i + b_i\right)^{d_i}}
$$

where $d_i$ the number of candidates in cell $i$

$n$ the total number of cells
Likelihood ratio method

To calculate confidence levels:

• Poisson probability for sg+bg and for bg only:

\[ P_{s+b} = \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)} (s_i + b_i)^{d_i}}{d_i!} \]

\[ P_b = \prod_{i=1}^{n} \frac{e^{-b_i} b_i^{d_i}}{d_i!} \]

• Sum over all configurations that give \( X \leq X_{\text{obs}} \) (less “signal-like”):

\[ CL_{s+b} = P_{s+b}(X \leq X_{\text{obs}}) = \sum_{X({\{d_i\}}) \leq X({\{d_{i,obs}\}})} P_{s+b} \]

\[ CL_b = P_b(X \leq X_{\text{obs}}) = \sum_{X({\{d_i\}}) \leq X({\{d_{i,obs}\}})} P_b \]

• Modified Frequentist confidence level: \( CL_s = \frac{CL_{s+b}}{CL_b} \)
Opening the box

One candidate found!

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Evaluation of the candidate

How likely is it that the candidate is due to known background?

- If there are 100 identical experiments, then 7 of them will have a candidate from a known bg source, that is as signal-like or more than our candidate.
- The sum of expected bg events in all cells with $s_i/b_i \geq 1$ to the one the event was found, is 0.077. The probability that they could produce one or more events is 0.074 (~ 7/100) $\equiv 1-CL_b$

The E949 candidate is more likely to be due to bg ("dirtier") than the E787 candidates...

<table>
<thead>
<tr>
<th>Candidate</th>
<th>E787A</th>
<th>E787C</th>
<th>E949A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.006</td>
<td>0.02</td>
<td>0.07</td>
</tr>
</tbody>
</table>
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**Combined result**

\[ BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \]

(68% CL interval)

E787 result:

\[ BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (157^{+1.75}_{-0.82}) \times 10^{-10} \]

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopped K(^+) ((N_K))</td>
<td>(5.9 \times 10^{12})</td>
<td>(1.8 \times 10^{12})</td>
</tr>
<tr>
<td>Total Acceptance</td>
<td>(0.0020 \pm 0.0002)</td>
<td>(0.0022 \pm 0.0002)</td>
</tr>
<tr>
<td>S.E.S.</td>
<td>(0.8 \times 10^{-10})</td>
<td>(2.6 \times 10^{-10})</td>
</tr>
<tr>
<td>Total Background</td>
<td>(0.14 \pm 0.05)</td>
<td>(0.30 \pm 0.03)</td>
</tr>
<tr>
<td>Candidate</td>
<td>E787A</td>
<td>E787C</td>
</tr>
<tr>
<td>(S_e/b_i)</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>(W_i = \frac{S_e}{S_e + b_i})</td>
<td>0.98</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Some more details…

\[ B(K^+ \rightarrow \pi^+\nu\bar{\nu}) > 0.42 \times 10^{-10} \text{ at } 90\% \text{ CL.} \]
\[ B(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 3.22 \times 10^{-10} \text{ at } 90\% \text{ CL.} \]

0.0055 < |V_{td}| < 0.0271

✓ The probability that known bg sources give a configuration of 3 events as signal-like as the 2 E787 + 1 E949 events or more, is 0.001

(compare to 0.077 for E949 alone)

? Central value, although smaller, is still \( \sim 2 \times \text{SM} \), but consistent within errors…

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Effect on unitarity triangle

Thanks to Gino Isidori

Limits from measurements of:

$\text{BR}(K^+ - \bar{\delta}^+ \bar{\pi}^-) : \quad \text{central value}$

$\cdots \cdots \text{68\% interval}$

$\cdots \cdots \text{90\% interval}$

$\hat{\epsilon}_{\Gamma}$

$|V_{ub}|/|V_{cb}|$

$\sin 2\hat{\epsilon}$

$\hat{\epsilon}_d$, $\hat{\epsilon}_s$ / $\hat{\epsilon}_d$ \{ Depend on $B_d$ mixing \}

Combined all but $K^+ - \bar{\delta}^+ \bar{\pi}^- (68\%, 90\%, 95\%)$
Narrowing of SM prediction assumes better measurement of $B_s$ mixing consistent w/ SM

✔ Obviously, more statistics are needed! → more E949 running would be desirable

✔ Analysis on PNN2 data (phase space below the $K^+\rightarrow\bar{\phi}\phi^*$ peak) currently in progress
PNN2 analysis (1)

- More phase space than PNN1
- Probes different part of $P_\delta$ spectrum $\rightarrow$ enhance validity of PNN1 result
- More background, scales the same as signal
Main bg mechanism: $K^+ \rightarrow \delta^+ \delta^i$ with $\delta^+$ scatter in target $\Rightarrow$

- Simultaneous shift in range AND momentum
- Photons head near beam direction, the weakest PV region of the detector
PNN2 analysis (3)

- **Goal:** sensitivity equal to PNN1, $s/b = 1 \Rightarrow$
  
  $2 \times$ acceptance and $5 \times$ rejection

- Improved PV: new detectors at small angles

- Improved algorithms to identify $\delta^+$ scatters in target

---

![Graph showing total rejection factor vs. total acceptance]
Conclusions

- E787 upgrade into E949 worked as expected
- One $K^+ \to \pi^+\nu\bar{\nu}$ candidate event observed, bringing the BR to $BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, which is still consistent with the SM
- Additional running needed for more influential results
- PNN2 analysis is under way
• Bg cannot be reliably simulated $\Rightarrow$ measure w/ data by inverting cuts and measuring rejection

$$\begin{align*}
\text{signal region} & \quad \begin{array}{c|c|c}
\text{cut1} & B & D \\
\hline
A & C & \\
\text{cut2} & & \\
\end{array}
\quad \begin{align*}
\text{if cut1, cut2 uncorrelated,} \\
A/B &= C/D \\
A &= BC/D
\end{align*}

\text{invert cut1 B+D events} & \quad \begin{array}{c|c|c}
B & D \\
A & C & \\
\end{array}
\quad \begin{align*}
\text{apply cut2 B events} & \quad \begin{array}{c|c|c}
B & D \\
A & C & \\
\end{array}
\quad \begin{align*}
\text{invert cut2 C+D events} & \quad \begin{array}{c|c|c}
B & D \\
A & C & \\
\end{array}
\quad \begin{align*}
\text{apply cut1 R = (C+D)/C} & \quad \begin{array}{c|c|c}
B & D \\
A & C & \\
\end{array}
\quad bg &= B/(R-1) \\
&= BC/D
\end{align*}
\end{align*}
\end{align*}
Analysis strategy (3)

- Verify bg estimates & check for correlations by *simultaneously* loosening both cuts and comparing observed and predicted number of events remaining. Construct background functions by varying *one cut at a time*, keeping the other inverted.
The E949 detector

First E949 results
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Delayed coincidence

\[ K^+ \rightarrow \mu^+\nu \text{ events} \]

\[ \pi^+ \text{ beam events} \]

First E949 results
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\[ \tilde{\delta}^+ \rightarrow \tilde{\iota}^+ \rightarrow e^+ \] identification

- \( E_i = 4.1 \text{ MeV}, R_\tilde{\iota} \sim 1 \text{ mm}, \hat{\delta}_\tilde{\delta} = 26 \text{ ns} \)
- \( E_e < 53 \text{ MeV}, \hat{\delta}_\iota = 2.2 \ \text{i} \text{s} \)
Toy MC for Junk code

BR dependence on s/b of cell where event is found:

![Graph showing BR dependence](image-url)
Pulse fitting in stopping counter

First E949 results
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Another view of the event
Combined (E787 & E949) 84% upper and lower limits and central value of BR for single simulated events in the 2002 data set, with variations of the assumed Kp2 bg component of ±30%