NA62: First result on $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

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Windows on the Universe

25th Anniversary Rencontres du Vietnam

Quy-Nhon, August 5 – 11, 2018
The NA62 Experiment

Fixed Target Experiment

Located at the North Area of CERN

75 GeV/c Secondary Hadron Beam

Carry on the tradition of Kaon experiments at CERN - SPS
### Kaon @ CERN - SPS

<table>
<thead>
<tr>
<th>Period</th>
<th>Experiment</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>'86 - '89</td>
<td>NA31</td>
<td>Hint of direct CP violation in Neutral Kaon decays</td>
</tr>
<tr>
<td>'97 - '01</td>
<td>NA48</td>
<td>$\varepsilon'/\varepsilon$: Proof of direct CP violation</td>
</tr>
<tr>
<td>'02</td>
<td>NA48/1</td>
<td>$K_s$ rare decays</td>
</tr>
<tr>
<td>'03 - '04</td>
<td>NA48/2</td>
<td>CP violation in Charge Kaons decays</td>
</tr>
<tr>
<td>'07 - '08</td>
<td>NA62-$R_K$ (NA48/3)</td>
<td>Lepton Universality ($R_K$)</td>
</tr>
<tr>
<td>'14 - '18</td>
<td>NA62</td>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay</td>
</tr>
</tbody>
</table>
Theoretical Motivation

FCNC loop process, highly suppressed, theoretically very clean


\[ Br_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11} \]

Previous Measurement (only 7 events) [BNL E787/E949: PRL101 (2008) 191802]

\[ Br_{Exp}(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3 \pm \frac{11.5}{10.5}) \times 10^{-11} \]
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Any deviation from the SM prediction is a hint of new physics
Theoretical Motivation

FCNC loop process, highly suppressed, theoretically very clean

*Expected 10% precision by NA62*

Well calculated inside the Standard Model

Previous Measurement (only 7 events) \cite{BNL E787/E949: PRL101 (2008) 191802}

\[
Br_{Exp}(K^+ \to \pi^+ \nu \bar{\nu}) = (17.3 \pm 11.5) \times 10^{-11}
\]

Any deviation from the SM prediction is a hint of new physics
Strategy and Apparatus

Signal:
✓ One beam $K^+$
✓ One $\pi^+$
✓ Nothing else

Background:
✗ Beam activity
✗ Other $K^+$ decays

- Precise kinematic reconstruction
- Hermetic Photon Detection
- Efficient PID for pion/muon discrimination
**Strategy and Apparatus**

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**SPS Protons**
- 400 GeV
- $10^{12}$ protons/s
- 3.5 s spill

**Secondary Beam**
- 75 GeV,
- $\Delta p/p \approx 1%$
- K (6%), p (23%), \(\pi\) (70%)
- 750 MHz

**Kaon Decays**
- $\approx 5$ MHz
- $4.5 \times 10^{12}$ per year
- $10^{-6}$ mbar vacuum

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**Beryllium Target**
Strategy and Apparatus

Kaon Tagging – CEDAR
45 MHz rate
time: 100 ps

Kaon Tracking – GTK
momentum: \(\frac{dp}{p} < 0.4\%\)
direction: \(\approx 0.016\) mrad

time: \(\approx 150\) ps

Beam Veto – CHANTI
time: \(\approx 1\) ns
Spectrometer – STRAW
momentum: $\frac{dP}{P} < 0.33\%$
direction: $\approx 10$ mrad
extracted vertex: $\approx 1$ mm

RICH
time: $< 100$ ps
muon rejection: 100

Calorimeters – LKr, HAC
Hadronc Shower Reconstruction
muon rejection: $10^5$

Fast Muon Veto
time: $\approx 300$ ps
Strategy and Apparatus

Small Angle – IRC, SAC
coverage: < 1 mrad

Large Angle – LAV
coverage: 8.5 – 50 mrad
time: ≈ 1 ns

EM Calorimeter – LKr
coverage: 1 – 8.5 mrad
time: ≈ 300 ps
resolution: \( \frac{\sigma_E}{E} (20 \text{ GeV}) < 1\% \)
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Analyzed Data

2016 Data Taking:
- Final commissioning of the apparatus
- About 50 days for physics
- 35 – 40% of nominal intensity
- About $1 \times 10^{11}$ $K^+$ decays for the analysis

Trigger Streams:
- “PNN”: Online K-ID, $\mu$ and $\gamma$ rejection
- “Control”: Minimum Bias

Analysis:
Data Samples:
- PNN: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Control: $K^+ \rightarrow \pi^+ \pi^0$ ($K_{2\pi}$), $K^+ \rightarrow \mu^+ \nu$ ($K_{\mu2}$), $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ ($K_{3\pi}$)

Blind Analysis: Signal and Control regions masked

In 2017 and 2018 more the 20x larger statistics (per year)
Selection

Event Selection:
- One track final state
- K⁺ - π⁺ Matching
- K⁺ decay in fiducial volume
- Pion Identification
- Photon Rejection
- Multi-Track Rejection

Performance:
- GTK – KTAG – RICH Timing: O(100 ps)
- π⁺ ID: ε_{μ⁺} = 10⁻⁸ vs ε_{π⁺} ≈ 64%
- Photon rejection: ε_{π₀} = 2.5 x 10⁻⁸
- σ_{m²_{miss}} ≈ 10⁻³ GeV²/c⁴
Selected Events

$\mathbf{m}_{\text{miss}}^2 [\text{GeV}^2/c^4]$

- $K_{3\pi}$
- $K_{2\pi}$
- $K_{\mu2}$

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

Data

Signal Region R2

Control Regions

$\pi^+$ momentum [GeV/c]
Signal Acceptance

- Evaluated from MC simulations: $A_{\pi\nu\nu} = (4.0 \pm 0.1)\%$

- Includes PID inefficiency and losses due to $\pi^+$ interactions
Random Veto

- Random Veto induced by photon and multiplicity/multi-track rejection
- Measured with $K^+ \rightarrow \mu^+\nu$ events
- $\langle \varepsilon_{RV} \rangle = 0.76 \pm 0.04$: independent from $p$, but dependent on the instantaneous intensity
Single Event Sensitivity (SES)

• Number of Kaon decays: $K_{2\pi}$ events selected in Control trigger (Downscaling D = 400)

• Same selection as for $K^+\rightarrow\pi^+\nu\nu$, but no photon rejection, different $m_{\text{miss}}^2$ region

$$SES = \frac{1}{N_K \times \left( A_{\pi\nu\nu} \times \epsilon_{RV} \times \epsilon_{\text{trigger}} \right)}$$

$$N_K = \frac{N_{\pi\pi} \times D}{A_{\pi\pi} \times BR_{\pi\pi}}$$

<table>
<thead>
<tr>
<th>Number of Kaon Decays</th>
<th>$N_K = (1.21 \pm 0.02) \times 10^{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance $K^+\rightarrow\pi^+\nu\nu$</td>
<td>$A_{\pi\nu\nu} = 0.040 \pm 0.001$</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>$\epsilon_{\text{trigger}} = 0.87 \pm 0.02$</td>
</tr>
<tr>
<td>Random Veto</td>
<td>$\epsilon_{RV} = 0.76 \pm 0.04$</td>
</tr>
<tr>
<td>SES</td>
<td>$(3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \times 10^{-10}$</td>
</tr>
<tr>
<td>Expected SM Events</td>
<td>$0.267 \pm 0.01_{\text{stat}} \pm 0.020_{\text{sys}} \pm 0.032_{\text{ext}}$</td>
</tr>
</tbody>
</table>
Backgrounds

Main background sources:

1. $K_{2\pi}$: BR = 20.67%
2. $K_{\mu 2}$: BR = 63.56%
3. $K_{e4}$: BR = 4.25 $\cdot$ 10^{-5}
4. Beam Induced
$K^+ \rightarrow \pi^+\pi^0(\gamma)$ Background

$$N_{\pi\pi}(\text{Region}) = N(\pi^+\pi^0) \times f^{\text{kin}}(\text{Region})$$

- Kinematic rejection uncorrelated wrt photon rejection
- $N(\pi^+\pi^0)$: remaining events under $K_{2\pi}$ peak after full selection
- $f^{\text{kin}}$ from $K_{2\pi}$ control sample with tagged $\pi^0$
- $f^{\text{kin}}(R1 + R2) \approx 10^{-3}$
- Radiative: $\pi^0 + \gamma$ 30x stronger photon rejection
$K^+ \rightarrow \pi^+\pi^0(\gamma)$ Background

$N_{\pi\pi}(R1 + R2) = 0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$

Expected control regions: $1.46 \pm 0.17 \Rightarrow$ Observed 1
$K^+ \rightarrow \mu^+ \nu(\gamma)$ Background

$$N_{\mu\nu}(\text{Region}) = N(\mu^+\nu) \times f^{\text{kin}}(\text{Region})$$

- Kinematic rejection uncorrelated wrt PID
- $N(\mu^+\nu)$: remaining events in $K_{\mu 2}$ region after full selection
- $f^{\text{kin}}$ from $K_{\mu 2}$ control sample with $\mu$-ID
- $f^{\text{kin}}(R1) \approx 10^{-5} \div 10^{-3}$
- $f^{\text{kin}}(R2) \approx 10^{-5}$
$K^+ \rightarrow \mu^+\nu(\gamma)$ Background

$$N_{\mu\nu}(R1 + R2) = 0.020 \pm 0.003_{\text{stat}} \pm 0.003_{\text{syst}}$$

Expected control regions: $1.02 \pm 0.16 \Rightarrow$ Observed 2
$K^+ \rightarrow \pi^+\pi^0e^+\nu$ Background

- Kinematics spanning over R2, correlated to topology
- Evaluated with about $4 \times 10^8$ MC events
- Validated with enriched data sample

$$N_{e4}(R2) = 0.018^{+0.024}_{-0.017}|_{stat} \pm 0.009_{syst}$$
Beam Related Background

Related to accidentals and/or interactions

1. $K^+$ decay along beam line

2. $\pi^+$ interactions

3. $K^+$ Interactions

4. Other similar topologies
Beam Related Background

Against Beam Background:
- K – π Matching
- Geometrical cut on back-projection
- \( Z_{\text{vertex}} \) and CHANTI

Background Estimation:
- Fully data driven
- Cut inversion
- Limited Statistics in 2016

\[ N_{\text{beam}}(R1 + R2) = 0.050^{+0.090}_{-0.030}|_{\text{stat}} \]
## Background Summary

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected Events (R1+R2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$ (SM)</td>
<td>$0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{ext}}$</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$ IB</td>
<td>$0.064 \pm 0.007_{\text{syst}} \pm 0.006_{\text{syst}}$</td>
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<td>$0.018^{+0.024}_{-0.017}</td>
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<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>$0.002 \pm 0.001_{\text{syst}} \pm 0.002_{\text{syst}}$</td>
</tr>
<tr>
<td>Beam Related</td>
<td>$0.050^{+0.09}_{-0.03}</td>
</tr>
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</table>
Result

\[ m^2_{\text{miss}} \text{ [GeV}^2/c^4] \]

\[ \pi^+ \rightarrow \pi^+\nu\bar{\nu} \text{ MC} \]

\[ \text{data} \]

\[ \pi^+ \text{ momentum [GeV/c]} \]
Result

1 Signal Event in R2

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

$\mathbf{data}$

$M^2_{\text{miss}}$ [GeV$^2$/c$^4$]

$\pi^+$ momentum [GeV/c]
Preliminary Results

<table>
<thead>
<tr>
<th>Observed Events</th>
<th>1</th>
</tr>
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<tr>
<td>SES</td>
<td>$3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}$</td>
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<tr>
<td>Expected Backgrounds</td>
<td>$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$</td>
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<tr>
<td>Expected Signals (SM)</td>
<td>$0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{ext}}$</td>
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$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 11 \times 10^{-10}$ @90% CL

$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @95% CL

✓ Expected Limit: $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 10 \times 10^{-10}$ @95% CL

✓ For comparison: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (2.8^{+4.4}_{-2.3}) \times 10^{-10}$ @68% CL

SM prediction: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$

BNL E747/E949: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
Prospects for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- **Data collection still on-going!**
  - In 2017 collected about 20x more data: currently processing and analyzing.
  - 2018 data taking expected to provide at least same statistics as 2017.

- **Selection efficiency improvements:**
  - Refine the analysis
  - Study of better handling of beam background (thanks to larger statistics)
  - Hardware mitigation of beam background (new collimator installed)

- **Expected about 20 SM events from the 2017-18 data sample**
Conclusions

- **NA62 Decay-in-Flight Technique works!**
- Analysis of 2016 data sample completed: 1 event observed

\[ Br(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 1.1 \times 10^{-10} \text{ @90\% CL} \]

- O(20) events expected from (2017+2018) data