\( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) – NA62 First Result

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*TRIUMF, Vancouver, BC
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Decay

NA62 Experiment

**K^+ \rightarrow \pi^+ \nu \bar{\nu} - In the Standard Model**

Flavour Changing Neutral Current:
- GIM suppression, involved CKM matrix elements are small
  \(|V_{ts}| \approx 0.039, |V_{td}| \approx 0.008\)

Hadronic matrix element related to \(K^+ \rightarrow \pi^0 e^+ \nu_e\) decay F. Mescia and C. Smith

[arXiv:0705.2025]

**In terms of the CKM parameters:**

\[
\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left[ \frac{|V_{cb}|}{40.7 \times 10^{-3}} \right]^{2.8} \left[ \frac{\gamma}{73.2^\circ} \right]^{0.74}
\]

\[
= (8.4 \pm 1.0) \times 10^{-11}
\]


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

E787/949 Collaboration [arXiv:0808.2459]
$K^+ \rightarrow \pi^+ \nu \bar{\nu} - $ Beyond the Standard Model

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been studied in many BSM scenarios. To name a few:

- **Littlest Higgs models**, M. Blanke et al [arXiv:1507.06316]
- **Lepton Flavour Violation models.** M. Bordone et al [arXiv:1705.10729]
Setup & Measurement Principle
NA62 is a kaon decay in flight experiment. The main objective is to measure $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ with a relative uncertainty around 10%.

(Also, heavy neutrinos, lepton flavour universality, exotic physics, etc.)

- 2005 Proposal,
- 2009 Approved,
- 2010 Technical design,
- 2012 Technical run,
- 2014–15 Pilot runs,
- 2016–18 Physics runs.

14 countries, 31 institutes, 214 authors.
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Measurement Principle

The missing mass squared, $m_{\text{miss}}^2 = (p_k - p_\pi)^2$, gives an handle on 92% of the background channels $\rightarrow$ Core aspect of the experiment.

- Identification of $K$ and $\pi$,
- Measurements of $K$ and $\pi$ momentum,
- Vetoes for $\gamma$ and $\mu$,
- $O (100\,\text{ps})$ timing capabilities for $K - \pi$ matching.

Main kaon backgrounds: $K^+ \rightarrow \mu^+ \nu_\mu \, (\gamma)$, $K^+ \rightarrow \pi^+ \pi^0 \, (\gamma)$, $K^+ \rightarrow \pi^+ \pi^+ \pi^-$, $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$. 
This talk: **2016 data**, 4 weeks of data taking, 35 – 40% of the nominal intensity.

**2017 data**, about 23 weeks of data taking, 60 – 65% of the nominal intensity, higher data quality $\rightarrow$ about $10 \times$ more data.

$\approx 1 \times 10^{11}$ good $K^+$ decays.  \hspace{2cm}  > 3 \times 10^{12}$ good $K^+$ decays.
Beam: 75 GeV/c ± 1%, $K$, $\pi$ and $p$ (6:70:23), 750 MHz.

Kaon & pion tracking, PID, calorimeters, hermetic photon vetos, muon veto, hodoscope and inelastic interactions veto → redundancy.

Minimize beam – gas interactions: vacuum $10^{-6}$ mbar.

Signal selection sketch: $K - \pi$ association, $15 < P_\pi < 35$ GeV/c, decay vertex in fiducial volume, no photon / muon / upstream activity.
Signal Selection
Kaon Identification & Tracking

Average beam intensity: 2016 $\rightarrow$ 35 – 40%, 2017–2018 $\rightarrow$ 60 – 65%.

KTag – Diff. Cherenkov counter,
- $N_2$ ($H_2$) gas radiator,
- Kaon time resolution $\approx$ 70 ps,
- $> 98\%$ $K$ ID efficiency.

GigaTracker – Silicon pixel tracker,
- Sensor surface is 60 by 27 mm – Match beam size,
- Thickness $\leq 0.5 \% X/X_0$ – Minimize beam induced background,
- Temporal resolution $< 150$ ps – $K^+$ – $\pi^+$ matching.

KTag and GTK : 75% $K^+$ reconstruction and identification efficiency.
Pion Tracking

Pion spectrometer – STRAW

Four STRAW chambers,

- 4 views / chamber, 448 straws / view,
- 1.3 m long dipole (0.9 Tm),
- straws are 2.1 m long, 9.8 mm in diam., 36 µm walls,
- $X/X_0 < 1.8%$,
- 70% Ar, 30% CO$_2$.

> 95% reconstruction efficiency.
Particle Identification

Pion / muon separation – RICH & Calorimeters

Ring-imaging Cherenkov detector,
- Ne gas radiator,
- Ring time resolution $\approx 80$ ps,
- $\mu/\pi$ separation $> 10^2$ ($15 < P < 35$ GeV/c).

Likelihood PID discriminant. Efficiency $2.5 \times 10^{-3} / 0.75$ for $\mu^+/\pi^+$.

Calorimeters,
- Electromagnetic calo. (LKr),
- Hadronic calo. (MUV1,2),
- Scintillator pads behind 80 cm Fe wall (MUV3).

MUV3 and BDT classifier. Efficiency $0.6 \times 10^{-5} / 0.77$ for $\mu^+/\pi^+$. 
Main cuts:

- No in-time signals in LAVs and SAV,
- No in-time signals in hodoscope and LKr (if not associated with $\pi^+$),
- Segment rejection in Straw.

Typical timing coincidence: $\pm 3/ \pm 5$ ns, energy dependent for LKr.

Fraction of $K^+ \rightarrow \pi^+ \pi^0$ passing the cuts: $2.5 \times 10^{-8}$. 
Signal and control regions blinded, selection developed on about 10% of the data set.
Single Event Sensitivity
Single Event Sensitivity (SES)

\[ K^+ \rightarrow \pi^+\pi^0 \text{ (from control data) used as normalization channel.} \]

\[
K^+ \rightarrow \pi^+\nu\bar{\nu} \text{ acceptance (MC)} \quad (4.0 \pm 0.1) \times 10^{-2} \\
\text{Random veto efficiency} \quad 0.76 \pm 0.04 \\
\text{Trigger efficiency} \quad 0.87 \pm 0.2
\]

\[
\text{SES} = (3.15 \pm 0.01_{\text{stat.}} \pm 0.24_{\text{syst.}}) \times 10^{-10}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta \text{SES} \ (10^{-10}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random veto</td>
<td>( \pm 0.17 )</td>
</tr>
<tr>
<td>Definition of ( \pi^+\pi^0 ) region</td>
<td>( \pm 0.10 )</td>
</tr>
<tr>
<td>Simulation of ( \pi^+ ) interactions</td>
<td>( \pm 0.09 )</td>
</tr>
<tr>
<td>( N_K )</td>
<td>( \pm 0.05 )</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>( \pm 0.04 )</td>
</tr>
<tr>
<td>Extra activity</td>
<td>( \pm 0.02 )</td>
</tr>
<tr>
<td>GTK pileup simulation</td>
<td>( \pm 0.02 )</td>
</tr>
<tr>
<td>Momentum spectrum</td>
<td>( \pm 0.01 )</td>
</tr>
<tr>
<td>Total</td>
<td>( \pm 0.24 )</td>
</tr>
</tbody>
</table>
Backgrounds Evaluation
Assume that $\pi^0$ rejection cuts and kinematic cuts are independent, kinematic rejection measured on $\pi^+\pi^0$ with tagged $\pi^0 (\gamma\gamma$ in LKr).

- Radiative tail in R2 estimated from MC,
- Single-$\gamma$ veto efficiency measured on data,
- $\pi^0\gamma$ rejection on the radiative tail estimated from data.

Radiative tail $\times 6$ bigger but $\pi^0\gamma$ rejection $\times 30.$

<table>
<thead>
<tr>
<th>Region</th>
<th>$N_{\pi\pi}^{\text{exp.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>$0.022 \pm 0.004 \pm 0.002$</td>
</tr>
<tr>
<td>R2</td>
<td>$0.037 \pm 0.006 \pm 0.003$</td>
</tr>
</tbody>
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<th>Region</th>
<th>$N_{\pi\pi\gamma}^{\text{exp.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0</td>
</tr>
<tr>
<td>R2</td>
<td>$0.005 \pm 0.005_{\text{syst.}}$</td>
</tr>
</tbody>
</table>
\[ K^+ \rightarrow \pi^+ \pi^- e^+ \nu \]

Estimated using MC, \( \approx 4 \times 10^8 \) events generated.

0.026 < \( m_{\text{miss}}^2 \) < 0.072 GeV\(^2/c^4\) region used for validation, free from other background processes.

Example: single \( \pi^- \) events, full \( \pi \nu \bar{\nu} \) selection, STRAW multiplicity cuts inverted.

\[ N_{\pi \pi e\nu}^{\text{exp.}} = 0.018^{+0.024}_{-0.017} \pm 0.009 \]
\[ K^+ \rightarrow \pi^+ \pi^+ \pi^- \]

Kinematic rejection in \( R_2 \leq 10^{-4} \), corrected for selection bias using the MC.

\[ N_{\pi \pi \pi}^{\text{exp.}} = 0.002 \pm 0.001 \pm 0.002 \]
Same approach as $K^+ \rightarrow \pi^+\pi^0(\gamma)$, assume that PID rejection cuts and kinematic cuts are independent. Kinematic rejection measured on $\mu^+\nu_\mu$ sample, applying the $\gamma$ rejection.

<table>
<thead>
<tr>
<th>Region</th>
<th>$N_{\mu\nu}(\gamma)^{\exp.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>$0.019 \pm 0.003 \pm 0.003$</td>
</tr>
<tr>
<td>R2</td>
<td>$0.0012 \pm 0.0002 \pm 0.0006$</td>
</tr>
</tbody>
</table>
Upstream Backgrounds

Estimation based on a “bifurcation” analysis.

\[ N_{\text{upstream}}^{\text{exp.}} = 0.050^{+0.090}_{-0.030} \]
Estimation based on a “bifurcation” analysis.

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\[ N_{\text{upstream}}^{\text{exp.}} = 0.050^{+0.090}_{-0.030} \]
<table>
<thead>
<tr>
<th>Process</th>
<th>R1</th>
<th>R2</th>
<th>R1+R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0 (\gamma)$</td>
<td>0.022</td>
<td>0.037</td>
<td>0.064 ± 0.007 ± 0.006</td>
</tr>
<tr>
<td>Upstream backgrounds</td>
<td>-</td>
<td>-</td>
<td>0.050$^{+0.090}_{-0.030}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^- e^+ \nu$</td>
<td>0</td>
<td>0.018</td>
<td>0.018$^{+0.024}_{-0.017}$ ± 0.009</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>0</td>
<td>0.0020</td>
<td>0.002 ± 0.001 ± 0.002</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu (\gamma)$</td>
<td>0.019</td>
<td>0.0012</td>
<td>0.020 ± 0.003 ± 0.003</td>
</tr>
<tr>
<td><strong>Total backgrounds</strong></td>
<td>-</td>
<td>-</td>
<td>0.15 ± 0.09 ± 0.01</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$ (SM)</td>
<td>0.069</td>
<td>0.198</td>
<td>0.267 ± 0.001 ± 0.020 ± 0.032</td>
</tr>
</tbody>
</table>
Preliminary Results
Preliminary Results
The Candidate in the RICH

Run 6646, burst 953, event 543854.
Cut based analysis of about 4 weeks worth of data.

\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ 95\% C.L.} \]

<table>
<thead>
<tr>
<th>Candidate</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_K)</td>
<td>((1.21 \pm 0.02) \times 10^{11})</td>
</tr>
<tr>
<td>SES</td>
<td>((3.15 \pm 0.01 \pm 0.24) \times 10^{-10})</td>
</tr>
<tr>
<td>Expected SM (K^+ \rightarrow \pi^+ \nu \bar{\nu})</td>
<td>(0.267 \pm 0.001 \pm 0.020 \pm 0.032_{\text{ext.}})</td>
</tr>
<tr>
<td>Expected background</td>
<td>(0.15 \pm 0.09 \pm 0.01)</td>
</tr>
</tbody>
</table>

Decay-in-flight technique works!
Prospects

More decays collected in 2017/2018:

- Data quality greatly improved in 2017/2018,
- Higher beam intensity (40–45% $\rightarrow$ 60–65% of nominal),
- 161 days in 2018, 217 days scheduled for 2018,
- More sophisticated data analysis (cut base $\rightarrow$ multi-variate).

Already $> 20 \times$ more data on tape.

About 20 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ SM events expected before LS2 (end of 2018).
The branching ratio, summing over the three neutrino flavours reads

\[ B\left(K^+ \rightarrow \pi^+ \nu \bar{\nu}\right) = \kappa_+\left(1 + \Delta_{EM}\right) \left[ \left(\frac{\text{Im} \lambda_t}{\lambda^5} X_t(X_t)\right)^2 + \left(\frac{\text{Re} \lambda_c}{\lambda} [P_c + \delta P_{c,u}] + \frac{\text{Re} \lambda_t}{\lambda^5} X_t(X_t)\right)^2\right] \], \quad (1)

where \( \lambda_i = V_{is}^* V_{id}, x_t = m_t^2/M_W^2 \). The parameter \( \Delta_{EM} \approx -0.3\% \) encodes the QED long distance radiative corrections [arXiv:0705.2025v2].

\[ \kappa_+ = (0.5173 \pm 0.0025) \times 10^{-10} \left(\frac{|V_{us}|}{0.225}\right)^8, \quad (2) \]

summarises the long-distance contributions extracted from the \( K^+ \rightarrow \pi^0 e^+ \nu_e \) decay [arXiv:0705.2025v2].
### Table: Error budget of the parameters entering in the $K \rightarrow \pi \nu \overline{\nu}$ branching ratio computation [arXiv:1503.02693].

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Error budget (%)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>6.7</td>
<td>-</td>
</tr>
<tr>
<td>$P_c$</td>
<td>1.8</td>
<td>Charm quark contribution</td>
</tr>
<tr>
<td>$\delta P_{c,u}$</td>
<td>2.9</td>
<td>Long distance charm-quark contribution</td>
</tr>
<tr>
<td>$X_t$</td>
<td>0.9</td>
<td>Top-quark contribution</td>
</tr>
<tr>
<td>Other</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>
Bifurcation Analysis

Estimate the number of background event in the signal region (A) using control regions $B'$, $C'$ and $D'$:

$A$: signal region

$A'$: control region, $B'$, $B''$, $C'$, $C''$ and $D'$: control samples.

If the two cuts are independent:

$$ \rightarrow A = \frac{B'C'}{D'} $$

$$ \rightarrow A' = \frac{B''C''}{D'} $$