Study of the branching ratio of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay with the NA62 experiment

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on behalf of the NA62 Collaboration

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Outline

- The NA62 experiment
- The FCNC decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Analysis strategy
- NA62 detector
- Signal region definition
- Results from 2016 data analysis
- Global Time Candidate
- Upstream Background
- Conclusions
The NA62 experiment

- **Main goal:** $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ with 10% precision.

- $\text{BR}_{\text{th}}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
  [Buras et al., JHEP 11(2015)033]

- $\text{BR}_{\exp}(K^+ \to \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$

- **Primary beam:** 400 GeV/c protons from SPS.

- **Secondary beam:** 75 GeV/c positively charged particles, 6% $K^+$.

- ~200 participants from ~30 institutes:
  Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC.
The FCNC decay $K^+ \to \pi^+ \nu\bar{\nu}$

- FCNC loop processes: $s\to d$ coupling and highest CKM suppression.
- Very clean theoretically.

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} = \begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

Weak eigenstates  Cabibbo Kobayashi Maskawa (CKM) matrix  Mass eigenstates

\[
\begin{vmatrix}
    V_{ud} & V_{ub}^* \\
    V_{cd} & V_{cb}^* \\
    V_{td} & V_{tb}^*
\end{vmatrix} = 0
\]

\[
V_{CKM} = \begin{pmatrix}
    1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
    -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
    A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]
The FCNC decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- **Custodial Randall-Sundrum** [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- **Simplified Z, Z' models** [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
Analysis strategy

- Timing between sub-detectors $O(100\text{ps})$
- Kinematic reconstruction
- Particle identification (PID)
- Muon and photon rejection
- $15 \text{ GeV}/c < P_\pi < 35 \text{ GeV}/c$
- Signal and control regions kept blind during the analysis

\[
M_{\text{miss}}^2 = (P_K - P_\pi)^2
\]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \to \mu^+\nu$</td>
<td>$(63.56\pm0.11)\times10^{-2}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^0$</td>
<td>$(20.67\pm0.08)\times10^{-2}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^+$</td>
<td>$(5.583\pm0.024)\times10^{-2}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^+\nu$</td>
<td>$(4.247\pm0.024)\times10^{-5}$</td>
</tr>
</tbody>
</table>
NA62 detector

- SPS 400 GeV/c proton beam.
- Secondary 75 GeV/c charged hadron beam (70% $\pi$, 24% p, 6% K), ~750MHz @ GTK, ~5 MHz K$^+$ decay rate.
NA62 detector

Differential Cherenkov for K+ ID

Charged veto

Large angle photon veto

π/μ ID

Photon veto

Muon veto

Target

KTAG

GTK

CHANTI

LAV

STRAW

LKr Calorimeter

MUV 1,2

Iron

MUV 3

SAC

Dump

Decay Region

Beam tracking

Silicon pixel

Spectrometer tracking

LKr Calorimeter Photon veto
NA62 detector

NA62 detector components:
- LKr
- CHOD
- RICH
- STRAW
Signal region definition

- Two signal regions, blind during the analysis.
- Background estimated extrapolating the tails of the distributions in the signal region.
2016 background summary

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events in R1 + R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$ (SM)</td>
<td>$0.267 \pm 0.001_{\text{stat}} \pm 0.029_{\text{syst}} \pm 0.032_{\text{ext}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$ IB</td>
<td>$0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu_\mu(\gamma)$ IB</td>
<td>$0.020 \pm 0.003_{\text{stat}} \pm 0.003_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-e^+\nu_e$</td>
<td>$0.018^{+0.024}_{-0.017}</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-$</td>
<td>$0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{syst}}$</td>
</tr>
<tr>
<td>Upstream background</td>
<td>$0.050^{+0.090}_{-0.030}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$</td>
</tr>
</tbody>
</table>

- One event observed in Region 2
  
  $\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90% CL
  $\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

- Processing of 2017-2018 data ongoing
- Expected ~20 more SM events.
Global Time Candidate

- Definition of the time of the event at software level.
- The detector I decided to use are KTAG, GTK and RICH:
  - Best time resolutions
  - Important and complementary informations about the event: the KTAG identifies the K in the beam, the GTK defines the upstream track and the RICH gives informations about the downstream track.
  - Contributions from other sub-detectors was considered, such as LKr, CHOD and NewCHOD.
- This time candidate can be used not only as a good starting point for the analysis, but also to redefine the upstream and downstream track, selecting the best hits in the definition of the sub-system candidate.
  - In particular, upstream background gives an important contribution to the total background.
Upstream background

- Possible explanations include:
  - $K^+$ decays upstream the decay region, matched to a pileup $\pi^+$ reconstructed in the GTK,
  - Interactions with material in the beam or in the GTK,
  - Accidental matching between the $K^+$ and the $\pi^+$.

- Evaluation of upstream background exploits a bifurcation technique.
  - At the moment, $K^+$ - $\pi^+$ association and box cut are the criteria to invert in order to select bifurcated samples.
  - Bifurcated samples used to evaluate the expected background in the signal region.
Conclusions

- One event found in R2 after unblinding the signal region in 2016 data set (0.27 expected).
- The analysis of 2016 data proves that the decay-in-flight technique of NA62 to study the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay works.
- Several improvements, both at hardware and software level, are foreseen.
  - 20 more signal events expected after analyzing the 2017 and 2018 data sets
- It is particularly important the monitoring and suppression of the upstream background.
  - A possible improvement could come from precise timing informations.
THANK YOU!
SPARES
Exotic searches

Dark Photon

Heavy Neutral Leptons

Axion-Like Particles