Measurement of the rare $K^+ \rightarrow \pi^+ \nu\nu$ decay from the NA62 experiment at CERN

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INFN - Sezione di Pisa and CERN
on behalf of the NA62 Collaboration

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax GMU, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC)

~200 participants

DIS 2022 - Santiago de Compostela
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Outline

• The NA62 experiment at CERN
• Study of the $K^+ \rightarrow \pi^+ \nu\nu$ decay
• Search for $K^+ \rightarrow \pi^+ X$
• Prospects and conclusions
Kaon decays at CERN

Kaon decay in flight experiments.
NA62: ~300 participants, ~30 institutes

| NA48/1 | 2000: $K_L$ only | $K_S$ H1 |
| NA48/2 | 2004: $K^+\!/K^-$ |
| NA62   | 2007: $K^{\pm}\!/K^{\pm}_{\mu2}$ tests |
|        | 2008: $K^{\pm}\!/K^{\pm}_{\mu2}$ tests |
| NA62   | 2014: pilot run |
|        | 2015: commissioning run |
| NA62   | 2016-18: $K^\to\pi^\nu\nu$ run |
|        | 2021: $K^\to\pi^\nu\nu$ run |

Earlier: NA31
1997: $e^+/e^-: K_L+K_S$
1998: $K_L+K_S$
1999: $K_L+K_S$ $K_S$ H1
2000: $K_L$ only $K_S$ H1
2001: $K_L+K_S$ $K_S$ H1
2002: $K_S$ hyperons
2003: $K^+/K^-$
2004: $K^+/K^-$

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The NA62 experiment

- **Main goal**
  - Measurement of BR \(K^+ \rightarrow \pi^+ \nu \nu\) with 10% accuracy

- **But also a broader physics programme**
  - Rare \(K^+\) decays
  - LNV/LFV in \(K^+\) decays
  - Hidden sector particles
  - **Dump mode: MeV-GeV hidden sector**
    - Dark photons
    - Heavy Neutral Leptons
    - Axions/Axion-like Particles
  - **With parallel high-efficiency trigger masks with a minimal load to the main stream**
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: clean theoretical environment

**FCNC loop processes:**
- $s \rightarrow d$ coupling
- Highest CKM suppression

**Very clean theoretically**
- No hadronic uncertainties
- Hadronic matrix element related to the precisely measured BR ($K^+ \rightarrow \pi^0 e^+ \nu$)

**SM predictions** [Buras et al. JHEP 1511 (2015) 33]

\[
BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \cdot \left( \frac{V_{cb}}{0.0407} \right)^{2.8} \cdot \left( \frac{\gamma}{73.2^0} \right)^{0.74} = (0.84 \pm 0.10) \cdot 10^{-10}
\]

\[
BR(K^0 \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \cdot \left( \frac{V_{ub}}{0.00388} \right)^2 \cdot \left( \frac{V_{cb}}{0.0407} \right)^2 \cdot \left( \frac{\sin \gamma}{\sin 73.2^0} \right)^{0.74} = (0.34 \pm 0.06) \cdot 10^{-10}
\]

$K \rightarrow \pi \nu \nu$ are the most sensitive probes to NP models among B and K decays

The combined measurement of $K^+$ and $K_L$ modes could shed light on the flavour structure of NP ($\Delta S=2 / \Delta S=1$ correlation)
K → πνν̄ NP sensitivity

Simplified Z, Z' models

More specific NP models

Littlest Higgs with T-parity

Custodial Randall-Sundrum
JHEP 0903 (2009) 108

LFU Violation
Isidori et al, EPJC (2017) 77

- Started to be probed at LHC, small effects in B physics.

Best probe of MSSM non-MFV [JHEP 0608 (2006) 064]
- E.g. non-MFV in up-squarks trilinear terms
- Still not excluded by the recent LHCb data.

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Previous status of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

E787/E949 @Brookhaven: 7 candidates $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
2 experiments, stopped kaon technique
Separated $K^+$ beam (710 MeV/c, 1.6MHz)
PID: range (entire $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain)
Hermetic photon veto system

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$


NA62, result from 2016+2017 data:

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.78 \times 10^{-10} (90\% \, CL)$$

JHEP 11 (2020) 042
NA62 goals and challenges

- Measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio
  - This requires at least $10^{13}$ Kaon decays
  - In-flight decay technique
  - $75$ GeV/c beam helps in background rejection
    - Event selection with $P_{\pi}<35$ GeV/c ($45$ GeV/c in region 2 for 2018 data)
    - i.e. $K_{\pi2}$ decays have around more than $\sim 40$ GeV of electromagnetic energy
    - $O(10^{12})$ rejection factor of common $K$ decays

Good tracking devices

Accurate measurement of the kaon momentum
Accurate measurement of the pion momentum
Missing mass cut: $O(10^5)$ rejection on $K_{\mu2}$, $O(10^4)$ on $K_{\pi2}$

Veto detectors

Photons: to reduce the background by a factor of $10^8$
Muons: add a rejection factor of $O(10^5)$

Particle identification

Identify kaons in the beam
Identify positrons
Additional $\pi/\mu$ rejection [$O(10^2)$]

Precise sub-ns timing

Kaon-pion time association
To reduce pileup
The NA62 detector

Beam
- Momentum: 75 GeV/c, 1% bite
- Divergence (RMS): 100 μrad
- Transverse Size: $60 \times 30\text{mm}^2$
- Composition: K+ 6%, π+ 70%, p 24%
- Nominal Intensity: $33 \times 10^{11}$ ppp (750 MHz at GTK3)

Fiducial region
- 60 m decay region
- $10^{-6}$ mbar vacuum
- Downstream rate $\sim 10$ MHz

Detector description:
JINST 12 P05025 (2017), arxiv:1703.08501
The NA62 detector

Upstream detectors (K⁺)
- **KTAG**: Differential Cherenkov counter for K⁺ ID
- **GTK**: Silicon pixel beam tracker
- **CHANTI**: Veto for inelastic beam-GTK3 interactions

Downstream detectors (π⁺)
- **STRAW**: Track spectrometer
- **CHOD**: Scintillator hodoscopes
- **LKr/MUV1/MUV2**: Calorimetric system
- **RICH**: Cherenkov for π/µ/e ID
- **LAV/LKr/IRC/SAC**: Photon veto
- **MU03**: Muon veto

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NA62 runs

2014: Pilot run
2015: Commissioning run
2016: Commissioning and physics run
Result published:

2017: 160 days of data taking
Result published:
JHEP 11 (2020) 042

2018: 217 days of data taking
Result published:
JHEP 06 (2021) 093
$K^+$ decay in-flight

- Signature: one incident kaon, 1 charged output track
- Missing mass distributions: $m_{miss}^2 = (P_K - P_{track(hyp ~ π^+)}))^2$
- Define two regions in $m_{miss}^2$ to accept candidate events
- 65 m long decay fiducial region, $15 < P_π < 35$ GeV/c
- Particle ID (Cherenkov detectors, calorimeters)
- Photon Veto

- Backgrounds:
  - Accidental beam activity
  - $K^+$ decay modes:
    
    $K^+ → π^+π^0(γ) \quad Br = 0.2067$
    $K^+ → μ^+ν(γ) \quad Br = 0.6356$
    $K^+ → π^+π^+π^- \quad Br = 0.0558$
    $K^+ → π^+π^-e^+ν \quad Br = 4.25*10^{-5}$
Data analysis

- **Analysis steps**
  - Selection
  - Determination of single event sensitivity (SES)
  - Estimation and validation of the expected background
  - Un-blinding of the signal regions

- **Selection**
  - $K^+$ decay into one charged particle
  - $\pi^+$ identification
  - Photon rejection
  - Multi track rejection

- **Performances**
  - GTK-KTAG-RICH timing: $O(100 \text{ ps})$
  - $\pi^+$ ID: $\varepsilon_\mu = 10^{-8}$; $\varepsilon_{\pi^+} \sim 64\%$
  - $\pi^0$ rejection $\varepsilon_{\pi^0} = \sim1.4 \cdot 10^{-8}$
  - $\sigma(m^2_{\text{miss}}) \sim 10^{-3} \text{ GeV}^2/c^4$
Single Event Sensitivity (SES)

- Determine Kaon flux from $K^+ \rightarrow \pi^+\pi^0$ selected with control trigger (downscale 400)
- Use the same $\pi\nu\nu$ selection, but without photon and multiplicity rejection and with missing mass cut modified

- Average random veto efficiency $\varepsilon_{RV} = (66\pm1)\%$
- Average trigger efficiency $\varepsilon_{trig} = (88\pm4)\%$
- Both efficiencies function of the instantaneous beam intensity, measured from the sidebands of the time distributions in the GTK
- All computations done in momentum bins and then summed

$$N_{\pi\nu\nu}^{exp} = N_{\pi\pi} \varepsilon_{RV} \varepsilon_{trig} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$ $$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$
Single Event Sensitivity (SES)

Integrated over beam intensity and $\pi^+$ momentum

$$SES = (0.111 \pm 0.007) \times 10^{-10}$$

$$N_{\pi NN}^{\exp} = 7.58 \pm 0.40_{\text{syst}} \pm 0.75_{\text{ext}}$$

External error from SM prediction for $BR = (0.84 \pm 0.10) \times 10^{-10}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>5%</td>
</tr>
<tr>
<td>MC Acceptance</td>
<td>3.5%</td>
</tr>
<tr>
<td>Random veto efficiency</td>
<td>2%</td>
</tr>
<tr>
<td>Instantaneous intensity</td>
<td>0.7%</td>
</tr>
<tr>
<td>Normalization background</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.5%</strong></td>
</tr>
</tbody>
</table>
Background suppression

Data driven estimation
\( K^+ \rightarrow \pi^+\pi^0 (\gamma), K^+ \rightarrow \mu^+\nu \) and \( K^+ \rightarrow \pi^+\pi^+ : \)

\[
\frac{N_{\pi\pi}^{\text{exp}} (\text{region})}{N_{\pi\pi}^{\mu\nu} (\text{region})} = N(\pi^+\pi^0)f^{\text{kin}}(\text{region})
\]

Expected events in the signal region, \( \pi\nu\nu \) selection

Data in \( \pi^+\pi^0 (\mu^+\nu) \) region, \( \pi\nu\nu \) selection (including \( \pi^0 \) rejection)

Fraction of \( \pi^+\pi^0 (\mu^+\nu) \) in signal region measured on control data

Control \( K^+ \rightarrow \pi^+\pi^0 \) data used to study the tails of the \( m^2_{\text{miss}} \) distribution and to measure \( f^{\text{kin}} \)

\( K^+ \rightarrow \pi^+\pi^- : \) Same procedure, but kinematic tails estimated with MC

\( K^+ \rightarrow \pi^+\pi^- e^+ e^- \), \( K^+ \rightarrow \pi^+\gamma \), \( K^+ \rightarrow \pi^0 e^+\nu : \) evaluation only with MC simulations normalized to the SES
Upstream background

$K^+$ decay/interaction in the achromat
Photons blocked by the collimators

$\pi^+$ detected in the straw, but it has scattered

Back extrapolation gives a fake vertex in the fiducial zone with an in-time pileup $K^+$

Use inverted $K$-$\pi$ matching to counts event from data

Estimation of the probability of occurrence from data/MC
Upstream background

In 2018 a new collimator was installed to help reducing upstream background.

Below track extrapolation at collimator in an enriched sample of upstream events.
Background evaluation

Estimation of the background using data
Validation in 6 control regions with blind analysis

After unmasking control regions good agreement between expected and observed events

<table>
<thead>
<tr>
<th>Background estimates summed over Region 1 and Region 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
</tr>
<tr>
<td>( \pi^+\pi^0 )</td>
</tr>
<tr>
<td>( \mu^+\nu )</td>
</tr>
<tr>
<td>( \pi^+\pi^- e^+\nu )</td>
</tr>
<tr>
<td>( \pi^+\pi^+\pi^- )</td>
</tr>
<tr>
<td>( \pi^+\gamma\gamma )</td>
</tr>
<tr>
<td>( \pi^0\ell^+\nu )</td>
</tr>
<tr>
<td>Upstream</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Total background = 5.42\( ^{+0.99}_{-0.75} \)
Opening the box

$17$ candidates observed

$7.58 \pm 0.85$ SM signal events expected with a background of $5.42^{+0.99}_{-0.75}$ events
$K^+ \rightarrow \pi^+ \nu\nu$ 2016+2017+2018 combined result

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed candidates</td>
<td>1</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Single event sensitivity</td>
<td>$(3.15 \pm 0.24) \cdot 10^{-10}$</td>
<td>$(3.89 \pm 0.21) \cdot 10^{-11}$</td>
<td>$(1.11 \pm 0.07) \cdot 10^{-11}$</td>
</tr>
<tr>
<td>Expected SM signal</td>
<td>$0.267 \pm 0.038$</td>
<td>$2.16 \pm 0.29$</td>
<td>$7.58 \pm 0.85$</td>
</tr>
<tr>
<td>Expected background</td>
<td>$0.152 \pm 0.090$</td>
<td>$1.46 \pm 0.33$</td>
<td>$5.42 \cdot 0.99^{-0.75}$</td>
</tr>
</tbody>
</table>

20 events observed in signal regions
$P(\text{bkg only}) = 3.4 \cdot 10^{-4}$
3.4 σ significance

9 categories: 2016, 2017, 2018 oldcol (S1) and 6 for 2018 newcol (S2)

Maximum log-likelihood fit using signal and background expectations in each category

$$BR(K^+ \rightarrow \pi^+ \nu\nu) = (10.6^{+4.0}_{-3.4} \pm 0.9_{\text{syst}}) \times 10^{-11} (68\% \text{ CL})$$

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The result

Most precise measurement of the $K^+ \rightarrow \pi^+ \nu \nu$ decay rate

Strongest evidence so far ($3.4 \sigma$) for its existence

Part of parameter space already ruled out

Exclusion of large $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ deviations from SM excluded

Grossman-Nir limit:
$\text{BR}(K_L \rightarrow \pi^0 \nu \nu) < 4.3 \times \text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$
$K^+ \rightarrow \pi^+ X, X$ invisible

- Search for feebly interacting particles in several models
  - Dark scalar mixing with Higgs boson
  - Scalars, like Alps, QCD axion, axiflavon
- Use the background shapes of $\pi^+\pi^-\nu\nu$ analysis: consider as SM background
- Peak search using the $m^2_{\text{miss}}$ observable for $M_X$ in the 0-260 MeV/c$^2$ range
- Improvements on previous limits over most of the $M_X$ range
- 90% UL on $\text{BR}(K^+ \rightarrow \pi^+ X)$ in $(10^{-11}-10^{-10})$
- Exclusion limits for dark scalars
  - Production and decay driven by mixing with Higgs
  - Assuming $X$ decays only to visible SM particles, then lifetime inversely proportional to the mixing
- Stringent constraints on the allowed region in the $(M_X, \sin^2\theta)$ plane
Conclusions

• The 2016-2017-2018 NA62 combined result for $K^+ \rightarrow \pi^+ \nu \nu$ has been presented
  - 20 events found

\[ BR(K^+ \rightarrow \pi^+ \nu \nu) = (10.6^{+4.0}_{-3.4}\ |_{stat} \pm 0.9\ |_{syst}) \times 10^{-11} (68\% \ CL) \]

• The experimental setup has been updated for the next data taking (2021-2025)
  - Data taken in 2021, 2022 run just started
  - New veto counter to further reduce upstream background
  - Upstream scintillator plane to help in reducing muon background in dump mode
  - Second HASC module to improve $\pi^0$ and $3\pi$ backgrounds

• Search for $K^+ \rightarrow \pi^+ X, X$ invisible
  - Improvement on the upper limit for the branching ratio
  - Stringent constraints on the allowed region in the ($M_X, \sin^2\theta$) plane
Thank you!

Artist’s view of the past installation activity...

... and of the current analysis work...