Recent results
from the NA62 experiment

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on behalf of the NA62 Collaboration

Outline:
- Introduction
- The NA62 experiment
- $K^+ \rightarrow \pi^+\nu\nu$ analysis
- Other analyses
- Summary & Prospects

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FCNC loop process: $s \rightarrow d\nu\nu$ quark transition

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

\[ Br(K_L \rightarrow \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11} \]

Extremely suppressed by GIM mechanism & theoretically well predicted

Charm contributes to theory errors

[Loops favor top contributions]

Hadronic matrix element from Ke3 via isospin rotation

K$^+ \rightarrow \pi^+ \nu\nu$ and New Physics

Test of SM

Indirect probes to explore high energy mass scale

Evidence of New Physics

- **Custodial Randall-Sundrum** [Blake, Buras, Dulin, Gemmler, Gori, JHEP 0903 (2009) 108]
- **Simplified Z,Z’ models** [Buras, Buttazzo, Knegjensi, JHEP 1511 (2015) 166]
- **Littlest Higgs with T-parity** [Blake, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- **Leptoquarks** [S. Fajfer et al. arXiv:1802.00786v1 (2018)]

Inputs to the unitary triangle independent from the B-physics
Experimental state of the art

Past experiments:

**E787/E949 at BNL**

**Kaon decay-at-rest technique**

(7 candidates)

\[ Br(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \]


**NA62 experiment at CERN SPS**

**Decay-in-flight technique**

2016+2017 data (1+2 observed events)

\[ Br(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 1.78 \times 10^{-10} @ 90\% C. \]

The NA62 experiment at the CERN SPS
The NA62 experiment at the CERN SPS

Broad physics program
- Main goal measure $K^+ \rightarrow \pi^+ \nu \nu$ branching ratio
- Rare and forbidden decays: LN and LF violation
- Precision measurements
- Exotics searches: dark photon, heavy neutral leptons, axion-like particles

~2.2 × 10^{18} POT collected

2016: 40% of nominal intensity
~0.12 × 10^{12} K+ decays in fiducial volume

2017: 60% of nominal intensity
~1.15 × 10^{12} K+ decays in fiducial volume

2018: 60%-70% of nominal intensity
~2.6 × 10^{12} K+ decays in fiducial volume
The NA62 Experiment: Kaon decay-in-flight technique

**Fixed target experiment**
- 400 GeV/c proton from SPS
- Beryllium target
- $1.9 \times 10^{12}$ protons/spill

**Beam Particles**
- Tag $K^+$: KTAG
- Cherenkov detector $\sigma_t \sim 70$ ps
- Beam Tracking: GigaTraKer
- Hybrid silicon pixels $\sigma_t \sim 200$ ps, $\sigma_p \sim 0.2$
- **CHANTI**: Anti-counter for beam- GTK3 inelastics

**Downstream Particles**
- Tracking: STRAW $\sigma_p \sim 0.3$
- **CHODs**: plastic scintillator for fast signal $\sigma_t = 200$ ps
- $\pi/\mu/e$ ID:
- **RICH**: Ring Imaging Cherenkov detector $\sigma_t = 100$ ps
- LKr/MUV1/MUV2: Calorimetric system
- Photon veto system: LKr/LAV/IRC/SAC
- Muon veto: MUV3

**Unseparated 75 GeV/c secondary beam**
- $p, \pi^+, K^+ (6\%)$ ($\Delta p/p = 1\%$)

**Decay Region**
- $105 < Z < 180$ m
- $\sim 5$ MHz $K^+$ decays

**2018 set-up**
- New Collimator
- Dipole Magnet
- CHOD
- MUV1,2
- CHANTI: Anti-counter for beam- GTK3 inelastics
- STRAW
- RICH
- LKr
- MUV1
- MUV2
- MUV3
- SAC
- IRG
- LAV
- IRC
- Dump
$K^+ \rightarrow \pi^+\nu\nu$: Analysis Strategy

**SM Br of $\mathcal{O}(10^{-10})$**
- High beam intensity

**Open kinematics**
- Powerful background suppression up to $\mathcal{O}(10^{11})$

- High time resolution $\mathcal{O}(100\text{ ps})$
- Muon suppression $> 10^7$ ($K^+ \rightarrow \mu^+\nu$)
- Photon suppression $> 10^7$ ($K^+ \rightarrow \pi^+\pi^0,\pi^0 \rightarrow \gamma\gamma$)
- Kinematic rejection $\mathcal{O}(10^4)$: accurate $m^2_{\text{miss}}$ resolution

- $15 < P_\pi < 45$ GeV/c
  - Guarantee high photon veto rejection ($P_{\pi^0} \geq 30$ GeV/c)
  - Guarantee good $\pi/\mu$ separation

$P_{K^+} \rightarrow \pi^+\nu\nu$

\[ m^2_{\text{miss}} = (P_{K^+} - P_\pi)^2 \]

$\sigma_{m^2} \sim 10^{-3}$ GeV$^2$/c$^4$

at the $K^+ \rightarrow \pi^+\pi^0$ peak

**Region 1**

**Region 2**
K^+ \rightarrow \pi^+\nu\nu: 2018 Analysis

Improvements in 2018

Detector:
- New upstream collimator has been installed to reduce upstream background

Analysis:
- Analysis performed in 7 separate categories
- Category definition depends on hardware configurations (S1 and S2) and momentum
- Selection optimize separately for each category ($\pi^+$ momentum dependent PID, MVA used)

Increase in global signal acceptance: from 3% of 2017 to:
- 4% before upstream collimator installation (20% of data taking)
- 6.4% after upstream collimator installation
2018 data after selection

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Single Event Sensitivity

\[ S.E.\ S = \frac{Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{N_{\text{exp}}^{\pi \nu \nu}} \]

\[ N_{\text{exp}}^{\pi \nu \nu} \sim N_{\text{obs}}^{\pi^+ \pi^0} \left( \frac{A_{\pi \nu \nu}}{A_{\pi^+ \pi^0}} \right) \frac{Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{Br(K^+ \rightarrow \pi^+ \pi^0)} \epsilon_{\text{trigger}} \epsilon_{\text{RV}} \]

**K^+ \rightarrow \pi^+ \pi^0** normalization channel

- **Acceptance** → Evaluated from MC. Ratio allows cancellation of systematic effects

- **Random Veto Efficiency**: losses of signal events because of the accidental presence of photons or/and charged particles

\[ N_{\text{exp}}^{\pi \nu \nu} = 7.58 \pm 0.40_{\text{syst}} \pm 0.75_{\text{ext}} \]

\[ S.E.\ S = \left( 1.11 \pm 0.07_{\text{syst}} \right) \times 10^{-11} \]
Background from $K^+$ decays

Exp. $\pi^+\pi^0$ events in control/signal regions after $\pi\nu\nu$ selection

\[
N_{\pi^+\pi^0}^{exp}(\text{region}) = N(\pi^+\pi^0) \times f_{\text{kin}}(\text{region})
\]

- Obs. events in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including $\pi^0$ rejection)
- Fraction of events in $\pi^+\pi^0$ control/signal regions in minimum bias data

- Same procedure for the $K^+\rightarrow\mu^+\nu_\mu$ and $K^+\rightarrow\pi^+\pi^+\pi^-$ backgrounds

- $K^+\rightarrow\pi^+\pi^-e^+\nu_e$, $K^+\rightarrow\pi^0l^+\nu$, $K^+\rightarrow\pi^+\gamma\gamma$ are evaluated with simulations normalized to the S.E.S

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Upstream Background

Interactions or decays of beam particles upstream of the FV

- $\pi^+$ is produced and reaches the downstream detectors
- no additional particles associated to the $\pi^+$
- a $K^+$ candidate is reconstructed and matched to a $\pi^+$

Background evaluation → Data-driven approach

Projection of the $\pi^+$ from the fake vertex to the entrance of the FV

Geometrical distribution used to define analysis cuts

$p$-value = 0.64
2018 data: Control regions unmasked and validated

Events observed in all control regions are consistent with expectations.
### 2018 data: Expected events in signal regions

<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>( 7.58 \pm 0.40 ) (<em>{\text{syst}}^{\text{syst}} \pm 0.75 ) (</em>{\text{ext}}^{\text{ext}} )</td>
</tr>
<tr>
<td>( K^{+} \rightarrow \pi^{+} \pi^{0} (\gamma) )</td>
<td>( 0.75 \pm 0.04 )</td>
</tr>
<tr>
<td>( K^{+} \rightarrow \mu^{+} \nu_{\mu} (\gamma) )</td>
<td>( 0.49 \pm 0.05 )</td>
</tr>
<tr>
<td>( K^{+} \rightarrow \pi^{+} \pi^{-} e^{+} \nu_{e} )</td>
<td>( 0.50 \pm 0.11 )</td>
</tr>
<tr>
<td>( K^{+} \rightarrow \pi^{+} \pi^{+} \pi^{-} )</td>
<td>( 0.24 \pm 0.08 )</td>
</tr>
<tr>
<td>( K^{+} \rightarrow \pi^{+} \gamma \gamma )</td>
<td>(&lt; 0.1 )</td>
</tr>
<tr>
<td>( K^{+} \rightarrow \pi^{0} l^{+} \nu )</td>
<td>(&lt; 0.001 )</td>
</tr>
<tr>
<td>Upstream background</td>
<td>( 3.30^{+0.98}_{-0.73} )</td>
</tr>
<tr>
<td>Total Background</td>
<td>( 5.28^{+0.99}_{-0.73} )</td>
</tr>
</tbody>
</table>
2018 data: Signal regions opened

5.3 background + 7.6 SM signal expected events $\rightarrow$ 17 events observed

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2018 data: Signal and background

$M_{\text{miss}}^2$ distribution for 2018 data integrated over the full $\pi^+$ momentum.

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Result: 2016+2017+2018 data

**2018 S1**: 80% of 2018 data after the installation of the new collimator
5 GeV/c $\pi^+$ momentum bins

**2018 S2**: 20% of 2018 data before the installation of the new collimator
integrated over full $\pi^+$ momentum range

Maximum Likelihood Fit using signal and background expectation in each category

$$Br(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-11} (3.5\sigma \text{ significance})$$
$K^+ \rightarrow \pi^+\nu\nu$: Historical context

Experimental measurement
Theoretical prediction

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$K \to \pi \nu \nu$: Grossman-Nir limit

Br($K_L \to \pi^0 \nu \bar{\nu}$) vs. Br($K^+ \to \pi^+ \nu \bar{\nu}$) × 10^{11}
$K^+ \rightarrow \pi^+\mu^+\mu^-$: Form Factors and Branching Ratio

FCNC decay described in the scope of ChPT, mediated by $K^+ \rightarrow \pi^+\gamma$
Together with $K^+ \rightarrow \pi^+e^+e^- \rightarrow$ Test of LFU

Analysis:
Precise 3-tracks vertex reconstruction + PID based on LKr + MUV3
FF parameters $a$ and $b$ extracted from fit of $z$ spectrum
Normalization: $K^+ \rightarrow \pi^+\pi^+\pi^- \rightarrow N_K \approx 6.76 \times 10^{12}$
Signal: $N(\pi^+\mu^+\mu^-) = 28011 \ (9 \times \text{NA48/2})$
Expected background: < 0.1%

Model-dependent
$\text{Br}(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.27 \pm 0.11) \times 10^{-8}$
PDG: $\text{Br}(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.4 \pm 0.6) \times 10^{-8}$

$\frac{d\Gamma}{dx dz} \propto G_F M^2_K (a + b z) + |W_{\pi\pi}(z)|^2,$
$z = m(\mu^+\mu^-)/M_K^2$
LNV & LFV at NA62: $K^+ \to \pi^\pm \mu^\mp e^\pm$

Interesting to search for New Physics effects, exploring high mass scale

Experimental strategy: precise three tracks vertex reconstruction + particle ID (LKr+MUV3)

Background: mis-ID $e^\pm \leftrightarrow \pi^\pm$ (data-driven), $\pi^\pm$ decay in flight

Normalization: $K^+ \to \pi^+ \pi^+ \pi^-$

2017+2018 Data:
1.32 x $10^{12}$ $K^+$ decays in FV

New Results

Br($K^+ \to \pi^+ \mu^- e^+$) < $6.6 \times 10^{-11}$ @ 90% C.L

Br($K^+ \to \pi^- \mu^+ e^+$) < $4.2 \times 10^{-11}$ @ 90% C.L

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E.g mediated by leptoquark
Heavy Neutral Lepton

HNL production: $K^+ \rightarrow \mu^+ N$, $K^+ \rightarrow e^+ N$

Peak search above continuous missing mass spectrum: $m_{\text{miss}}^2 = (P_K - P_l)^2$

Final results
PLB 708 (2020) 135599

New Results
½ data sample
Summary & Prospects

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ NA62 results from Run1(2016+2017+2018)
  \(20(1+2+17) \text{ events observed with total expected background } \sim 7\)
  \(\text{most precise measurement so far}\)
  \[B_r(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5} \pm 0.3) \times 10^{-11}\]
  \(\text{The result is compatible with the SM prediction within one standard deviation}\)

- New results from analyses on rare and forbidden kaon decays as well as on exotic searches have been shown

Towards 2021

- NA62 will resume data taking in 2021
- Upgrade of the experiment setup. Installation of:
  \(\text{additional beam spectrometer station}\)
  \(\text{upstream veto counter to reduce upstream background}\)
  \(\text{new calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background}\)