Results from NA62

R. Fantechi

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

FPCP 2020
June 8th-12th, 2020
Kaon decays at CERN

earlier: NA31

1997: $e^+e^- \rightarrow K_L + K_S$

1998: $K_L + K_S$

1999: $K_L + K_S$

2000: $K_L$ only

2001: $K_L + K_S$

2002: $K_S$ / hyperons

2003: $K^+ / K^-$

2004: $K^+ / K^-$

2007: $K_{\mu 2} / K_{\mu 2}$ tests

2008: $K_{\mu 2} / K_{\mu 2}$ tests

2014: pilot run

2015: commissioning run

2016 – : $K^+ \rightarrow \pi^+ \nu \nu$ run

R. Fantechi - FPCP 2020 - June 9th 2020
**K^+ \to \pi^+ \nu\bar{\nu}: clean theoretical environment**

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**FCNC loop processes:**
- s→d coupling
- Highest CKM suppression

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

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

\[
BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \cdot \left( \frac{V_{cb}}{0.0407} \right)^2 \cdot \left( \frac{\gamma}{73.2^0} \right)^{0.74} = (0.84 \pm 0.10) \cdot 10^{-10}
\]

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

**K \to \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 → πν̅ν 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 $K^+ \to \pi^+\nu\bar{\nu}$

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

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


NA62, result from 2016 data:
1 event observed
Background: $0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$ events

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


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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
    - i.e. $K_{ π^+}$ decays have around more than ~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 $K_{μ2}$, $O(10^4)$ on $K_{π2}$

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 $π/μ$ 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 $\sim 10 \text{ MHz}$

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
- **MU0**: Muon veto
NA62 runs

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

Result published:
arXiv.1811.08508

2017: 160 days of data taking
This talk, paper in preparation

2018: 217 days of data taking
Analysis on going
**K⁺ decay in-flight**

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

**Backgrounds:**

- **Accidental beam activity**
- **K⁺ decay modes:**
  
  \[
  \begin{align*}
  K^+ &\to \pi^+\pi^0 \,(\gamma) \quad \text{Br} = 0.2067 \\
  K^+ &\to \mu^+\nu \,(\gamma) \quad \text{Br} = 0.6356 \\
  K^+ &\to \pi^+\pi^+\pi^- \quad \text{Br} = 0.0558 \\
  K^+ &\to \pi^+\pi^-e^+\nu \quad \text{Br} = 4.25 \times 10^{-5}
  \end{align*}
  \]
2017 data analysis

• $19 \cdot 10^{11}$ ppp on target

• $2 \cdot 10^{12}$ $K^+$ decays useful for $\pi\nu\nu$

• Blind analysis procedure
  - Signal and control regions kept masked for the whole analysis

• Main trigger streams:
  - $\pi\nu\nu$, control

• Offline analysis
  - $\pi\nu\nu$ sample
  - Control samples
    • $K^+ \rightarrow \pi^+\pi^0$
    • $K^+ \rightarrow \mu^+\nu$
    • $K^+ \rightarrow \pi^+\pi^+\pi^-$

Analysis steps

- Selection
- Determination of single event sensitivity (SES)
- Estimation and validation of the expected background
- Un-blinding of the signal regions and results
Kaon decay selection

• 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 $\varepsilon_{\pi^0} = \sim 1.4 \cdot 10^{-8}$
  - $\sigma(m_{\text{miss}}^2) \sim 10^{-3} \text{ GeV}^2/c^4$
Data after selection

Control and signal regions MASKED

- $\pi^+\pi^0$ Control Regions
- $\pi^+\pi^+\pi^-$ Control Region
- $\mu^+\nu$ Control Region
- High - P control region
- Upstream background control region

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

$\pi^+$ momentum [GeV/c]
Single Event Sensitivity (SES)

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

$$N_{\pi\nu\nu}^{\text{exp}} = N_{\pi\pi} \varepsilon_{RV} \varepsilon_{\text{trig}} \frac{A_{\pi\nu \nu}}{A_{\pi\pi}} \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{\text{exp}}}$$

Intensity measurements from the sidebands of the GTK
Single Event Sensitivity (SES)

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

$$SES = (0.389 \pm 0.021) \times 10^{-10} \quad N_{\pi\nu\nu}^{\text{exp}} = 2.16 \pm 0.12 \pm 0.26_{\text{ext}}$$

External error from BR = $0.84 \pm 0.10$

<table>
<thead>
<tr>
<th>Error budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
</tr>
<tr>
<td>L0 trigger</td>
</tr>
<tr>
<td>Acceptance</td>
</tr>
<tr>
<td>Random veto</td>
</tr>
<tr>
<td>L1 trigger</td>
</tr>
<tr>
<td>Normalization background</td>
</tr>
</tbody>
</table>
**K^+ → π^+π^0 (γ) and K^+ → μ^+ν background**

\[ N_{ππ}^{exp}(region) = N(π^+π^0)f^{kin}(region) \]

- **Expected events in the signal region, \( πνν \) selection**
- **Data in \( π^+π^0 \) (\( μ^+ν \)) region, \( πνν \) selection (including \( π^0 \) rejection)**
- **Fraction of \( π^+π^0 \) (\( μ^+ν \)) in signal region measured on control data**

\[ N_{μν}^{exp}(region) = N(μ^+ν)f^{kin}(region) \]
$K^+ \rightarrow \pi^+\pi^-e^+\nu \ (K_{e4})$ background

- Measured branching ratio: $4.247(24) \cdot 10^{-5}$
- Topology-correlated kinematics spanning Region 2
- MC-based background estimation, $2 \cdot 10^9$ events generated
- Validation of MC done with data using enriched $K^+ \rightarrow \pi^+\pi^-e^+\nu$ sample

$$N_{K_{e4}}^{bg} = 0.12 \pm 0.05_{st} \pm 0.03_{sy}$$
Upstream background

$K^+ (75 \text{ GeV})$

$K^+$ 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

$$N_{upstream}^{bg} = 0.9 \pm 0.2_{st} \pm 0.2_{sy}$$
# Background summary

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events in R1+R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K \rightarrow \pi\nu\nu$ (SM)</td>
<td>$2.16 \pm 0.12_{\text{stat}} \pm 0.26_{\text{ext}}$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$1.5 \pm 0.2_{\text{stat}} \pm 0.2_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$ (γ)</td>
<td>$0.29 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu$ (γ)</td>
<td>$0.15 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>$0.02 \pm 0.02_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-e^+\nu$</td>
<td>$0.012 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \ell^+\pi^0\nu$</td>
<td>Negligible</td>
</tr>
<tr>
<td>Upstream background</td>
<td>$0.9 \pm 0.2_{\text{stat}} \pm 0.2_{\text{syst}}$</td>
</tr>
</tbody>
</table>
Opening the box

Two events observed in signal region

NA62 Preliminary
# $K^+ \rightarrow \pi^+ \nu\nu$ 2016+2017 result

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed candidates</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Single event sensitivity</td>
<td>$(0.389 \pm 0.021) \cdot 10^{-10}$</td>
<td>$(3.15 \pm 0.24) \cdot 10^{-10}$</td>
</tr>
<tr>
<td>Expected SM signal</td>
<td>$2.16 \pm 0.12 \pm 0.26_{\text{ext}}$</td>
<td>$0.27 \pm 0.02 \pm 0.03_{\text{ext}}$</td>
</tr>
<tr>
<td>Expected background</td>
<td>$1.5 \pm 0.3$</td>
<td>$0.15 \pm 0.09$</td>
</tr>
</tbody>
</table>

**Upper limits (CLs methods)**

- **Observed**
  \[ \text{BR}(K \rightarrow \pi\nu\nu) < 1.85 \cdot 10^{-10} \text{ @ 90\% CL} \]
- **Expected (bkg only)**
  \[ \text{BR}(K \rightarrow \pi\nu\nu) < 1.32 \cdot 10^{-10} \text{ @ 90\% CL} \]

**Two sides 68\% band**
\[ \text{BR}(K \rightarrow \pi\nu\nu) = (0.47^{+0.72}_{-0.47}) \cdot 10^{-10} \]
K$^+ \rightarrow \pi^+\nu\bar{\nu}$ 2016+2017 result
Analysis improvements

• The used event selection aimed for the highest background rejection
  - Strong cuts, acceptance reduced to a few %
• Reoptimization of the analysis to improve signal efficiency:
  - Optimization of signal region and optimization of PID
  - Improvements of selection against upstream background
• Signal improvement by a factor ~2
• Background level scales accordingly
• More optimizations being studied
  - Improvement of upstream background using a BDT with pion informations
  - Improve the K-π matching, with a better likelihood or with neural networks
  - Reduce the random veto (42% loss in 2018) by
    • optimising photon rejection in LAV
    • developing LKr reconstruction specific for veto purpose
    • refining event reconstruction in small angle calorimeters
    • optimising multiplicity rejection algorithm
Improvements for the next runs

• Few additions to the experimental setup
  - Rearrangement of the beam line around the achromat and addition of a 4th GTK station
    • To improve the efficiency of K-π matching
    • To improve the rejection of the upstream background
  - Addition of a veto counter before and after the final collimator
    • To improve the rejection of the upstream background
  - Installation of a large scintillator tile hodoscope in front of the decay volume
    • To improve background rejection in dump mode
    • To reduce the trigger rate in some rare decay modes
  - Addition of a second HASC module
    • To further reduce photon background

• Plan to run from 2021 to 2024
\[ \pi^0 \rightarrow \text{invisible} \]

- In the SM, \( \text{BR}(\pi^0 \rightarrow \nu\bar{\nu}) \sim O(10^{-24}) \), so any observation \( \rightarrow \text{BSM} \)
- Present limit is \( 2.7 \cdot 10^{-7} \) at 90% CL, from BNL experiments
- Profit from hermetic photon veto
- Same \( \pi^\nu\nu \) selection and trigger
- Evaluate a-priori the \( \pi^0 \) suppression in \( \pi^+\pi^0 \) kinematic region
- Use \( \pi^0 \rightarrow \gamma\gamma \) as normalization channel

- Expected background: \( 10^{+22}_8 \) events
- Observed: 12 events

Preliminary result: \( \text{BR}(\pi^0 \rightarrow \gamma\gamma) < 4.4 \cdot 10^{-9} \) @ 90% CL

A factor 60 better wrt to previous measurements
$K^+ \rightarrow \pi^+ X$, $X$ invisible

- Search for feebly interacting particles in several models
  - Dark scalar mixing with Higgs boson
  - Scalars, like Alps, QCD axion, axiflavon
- Use the same selection, normalization and background evaluation of $\pi\nu\nu$ analysis
- Generate signal with two body decay for 200 mass hypotheses to compute acceptance
- Shape analysis on $m^2_{\text{miss}}$
- Fully frequentist approach, profiled likelihood test statistic
- Background parameterized with polynomial functions from $\pi\nu\nu$ analysis
- Signal shape: Gaussian, number of expected signal events obtained as in $\pi\nu\nu$ analysis.
**K^+ → π^+ X, X invisible - Results**

\[
\begin{align*}
\text{BR}(K^+ → π^+ X) &< (0.5-2.0) \cdot 10^{-10} @ 90\% \text{ CL} \quad \text{for } m_X \in [0,100] \text{ MeV/c}^2 \\
\text{BR}(K^+ → π^+ X) &< (0.4-1.4) \cdot 10^{-10} @ 90\% \text{ CL} \quad \text{for } m_X \in [160,260] \text{ MeV/c}^2
\end{align*}
\]

*Paper in preparation*

Assuming X decays to a visible SM particle, detected by NA62

Evaluate the BR upper limit as a function of \( m_X \)

10 times better than E949 for \( m_X \in [160,260] \)
Conclusions

- A preliminary result from the analysis of the NA62 2017 data has been presented
  - 2 event found with an expected background of 1.5
  - The combination of 2016 and 2017 data gives an upper limit for the branching ratio of $1.85 \times 10^{-10}$
  - The two sides 68% band is $0.47^{+0.72}_{-0.47} \times 10^{-10}$

- The analysis of 2018 data is progressing
  - Improvements have been studied using the 2017 data

- The experimental setup is being updated for the next data taking (2012-2024)

- 2017 data have been used to search for exotic processes
  - 60 times improvement in the limit for $\pi^0 \rightarrow$ invisible
  - Improved limits on $K^+ \rightarrow \pi^+ X$, X invisible
Thank you!

Artist’s view of the past installation activity…

… and of the current analysis work…
Spares
Beam dump mode

Dumping the beam ahead of the detector will allow to produce B, D and K mesons decaying promptly to exotics mediators and SM particles.

Exotic particles could be produced also in the dump.

Exotics searches extended up to $m \sim 1.7$ GeV.

$3 \times 10^{16}$ POT has been collected in dump mode in 2017-2018. Analysis is ongoing to study the backgrounds.

Runs in dump mode are foreseen during run 3 for a total of $O(10^{18})$ POT.

An additional veto counter ahead of the decay volume will improve the background rejection, mainly on not-closed channels.
Dark scalar

\[ S \rightarrow \mu^+\mu^- \]

\[(\mu S + \lambda S^2)H^+H \]

\[ \mu = \sin \theta \]

\[ \lambda = 0 \]

Search for two opposite sign charged tracks in the NA62 fiducial volume

Expected 90% CL exclusion contours
- Including trigger/acceptance/selection efficiencies
- Assume zero background
Dark photon

\[ A' \rightarrow e^+e^-, \quad A' \rightarrow \mu^+\mu^- \]

Search for two opposite sign charged tracks in the NA62 fiducial volume

Possible improvement on current limits

Here only p-Be target considered

Including direct QCD production of \( A' \) and \( A' \) production in the dump, the sensitivity will be higher

Expected 90% CL exclusion contours

- Including trigger/acceptance/selection efficiencies
- Assume zero background
Heavy neutral leptons

\[ D/D_s \rightarrow \ell^+ \nu_H, \, \nu_H \rightarrow \pi e, \, \nu_H \rightarrow \pi \mu \]

Also the \( \tau \) coupling can be probed

Expected 90% CL exclusion contours
- Including trigger/acceptance/selection efficiencies
- Assume zero background
Axion-like particles (ALPs)

Production via elastic scattering of beam protons on the dump

Coupling to photons is the main one

Search for decay $A \rightarrow \gamma \gamma$
Signature: 2 photons in the LKr calorimeter

Expected 90% CL exclusion contours
- Including trigger/acceptance/selection efficiencies
- Assume zero background