NA62 status and prospects

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on behalf of the NA62UK collaboration

Outline:

1) Physics at kaon experiments: $K \rightarrow \pi \nu \bar{\nu}$ decays and beyond
2) NA62 status, performance, UK involvement.
3) Prospects for CERN kaon experiments beyond 2018.
4) Overview of the recent results.
5) Summary

PPAP community meeting
Birmingham • 26 July 2016
Rare kaon decays: $K \rightarrow \pi \nu \bar{\nu}$

**SM: box and penguin diagrams**

- Ultra-rare decays with the highest CKM suppression:
  \[ A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5 \]

- Hadronic matrix element related to a measured quantity ($K^+ \rightarrow \pi^0 e^+ \nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from $B - \bar{B}$ mixing or $B^0 \rightarrow \rho \gamma$.

**SM branching ratios**

*Buras et al., JHEP 1511 (2015) 033*

<table>
<thead>
<tr>
<th>Mode</th>
<th>$BR_{SM} \times 10^{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma)$</td>
<td>$9.11 \pm 0.72$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>$3.00 \pm 0.31$</td>
</tr>
</tbody>
</table>

The uncertainties are largely parametric (CKM)

Theoretically clean, almost unexplored, sensitive to new physics.

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NA62 aim: collect $O(100)$ SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

**Signature:** high momentum $K^+ (75 \text{GeV/c}) \rightarrow$ low momentum $\pi^+ (15–35 \text{ GeV/c})$.

**Advantages:** max detected $K^+$ decays/proton ($p_K/p_0 \approx 0.2$); efficient photon veto (>40 GeV missing energy).

Un-separated beam (6% kaons) $\rightarrow$ higher rates, additional background sources.

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Broader programme (1)

Neutrino oscillations discovery (1998)

First non-SM phenomenon:
1) Lepton Flavour Violation;
2) non-zero neutrino mass.

New physics scenarios involving LFV:
✓ Neutrino is a Majorana fermion (identical to antineutrino)
✓ Heavy (possibly sterile) neutrino states
✓ Supersymmetry with R-parity violation or RH neutrinos

Astrophysical consequences:
✓ Dark matter, nucleosynthesis, Supernova evolution, ...

❖ Search for forbidden states with lepton pair (ee, μμ, μe):

\[
\begin{align*}
K^+ & \rightarrow \pi^+ \mu^+ e^- \\
K^+ & \rightarrow \pi^+ \mu^- e^+ \\
K^+ & \rightarrow \pi^- \mu^+ e^+ \\
K^+ & \rightarrow \pi^- e^+ e^+ \\
K^+ & \rightarrow \pi^- \mu^+ \mu^+ \\
K^+ & \rightarrow \mu^- \nu e^+ e^+ \\
K^+ & \rightarrow e^- \nu \mu^+ \mu^+ \\
K^+ & \rightarrow \pi^+ \pi^0, \quad \pi^0 \rightarrow \mu^+ e^- \\
K^+ & \rightarrow \pi^+ \pi^0, \quad \pi^0 \rightarrow \mu^- e^+ 
\end{align*}
\]
Neutrino minimal SM (νMSM) = SM + 3 right-handed neutral heavy leptons.

[Asaka et al., PLB 631 (2005) 151]

Masses: \( m_1 \sim 10 \text{ keV} \) [DM candidate]; \( m_{2,3} \sim 1 \text{ GeV} \).

HNLs observable via production and decay.

\( |U_{l4}|^2 \)

Astrophysical & cosmological constraints on \( m_1, m_{2,3} \)

X-ray constraints \( \tau > 10^{24} \text{ s} \)

Phase-space density constraints

\( R(m_N) = \frac{\Gamma(K^+ \rightarrow l^+\nu_H)}{\Gamma(K^+ \rightarrow \mu^+\nu_H)} / |U_{l4}|^2 \)

HNL production, kinematic factor:

\( K^+ \rightarrow \mu^+\nu_H \): helicity suppressed \((\sim 10^{-5})\) for \( m_N \rightarrow 0 \)

\( K^+ \rightarrow e^+\nu_H \): helicity suppressed \((\sim 10^{-5})\) for \( m_N \rightarrow 0 \)

\( R. \ Shrock \ PLB96\ (1980) 159 \)

\( PLB698\ (2011) \ 105 \)

Baryon asymmetry of the Universe

BBN \( \tau < 0.1 \text{ s} \)

Big-Bang nucleosynthesis

Seesaw

\( Shaposhnikov, \ JHEP \ 0808\ (2008) \ 008 \)

NA62 status and UK involvement
CERN NA48/NA62 experiments

Kaon decay in flight experiments.

**NA62**: currently ~200 participants, ~30 institutions.

**NA62UK**: Birmingham, Bristol, Glasgow, Liverpool (12% of participants).

Earlier: NA31

- **1997**: $\varepsilon'/\varepsilon$: $K_L+K_S$
- **1998**: $K_L+K_S$
- **1999**: $K_L+K_S$ [K S HL]
- **2000**: $K_L$ only [K S HL]
- **2001**: $K_L+K_S$ [K S HL]
- **2002**: $K_S$/hyperons
- **2003**: $K^+/K^-$
- **2004**: $K^+/K^-$
- **2007**: $K^+e_2/K^+\mu_2$ tests
- **2008**: $K^+e_2/K^+\mu_2$ tests
- **2014**: pilot run
- **2015–**: data taking

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The NA62 experiment

Un-separated hadron (p/π+/K+) beam: 400GeV SPS protons → 75GeV (±1%) kaons; 800MHz → 45MHz kaons → 5MHz decays in fiducial volume

NA62UK (funded by ERC)

Target

KTAG

(Cherenkov kaon tagger) <80ps timing

Un-separated hadron (p/π+/K+) beam: 400GeV SPS protons → 75GeV (±1%) kaons; 800MHz → 45MHz kaons → 5MHz decays in fiducial volume

Expected single event sensitivities (SES): \( \sim 10^{-12} \) (\( \sim 10^{-11} \)) for \( K^\pm (\pi^0) \) decays.

Kinematic rejection factors (limited by beam pileup and tails of MCS): \( 5 \times 10^3 \) for \( K^+\rightarrow\pi^+\pi^0 \), \( 1.5 \times 10^4 \) for \( K\rightarrow\mu^+\nu \).

Hermetic photon veto: \( \sim 10^8 \) suppression of \( \pi^0\rightarrow\gamma\gamma \).

Particle ID (RICH+LKr+MUV): \( \sim 10^7 \) muon suppression.
Minimum bias (~1% intensity) and $K_{\pi\nu\nu}$ test runs taken in 2015. Most systems commissioned and meet the design requirements.

Running at 20% intensity now, planning ~50% intensity later in 2016 (max intensity is currently limited by SPS capabilities)

Expect to reach a few SM $K_{\pi\nu\nu}$ events sensitivity by the end of 2016
Gigatracker information not used in this study.
Photon veto criteria not applied on purpose.
Kinematic & time resolutions are close to the design.
KTAG operation in 2015

The first NA62 detector to be commissioned; performance exceeds specifications

Funded by ERC

Number of PMT signals per $K^+$
Mean hits/$K^+$: 20
Mean nominal rate/channel: 2.3 MHz

Single PMT.
Central peak: 160ps; RMS=300ps.

PMT time resolution
$\sigma(K\text{ time}) = 70$ps

Kaon ID efficiency vs sectors in coincidence

$95\%$

working point: 5-fold coincidence

scattering in 1st dynode

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NA62: UK contributions

Hardware and trigger:
- full responsibility for the **KTAG subdetector**;
- full responsibility for the **Run Control** system;
- development and operation of **L0 muon+hodoscope+RICH trigger**;
- development and operation of the **high-level software trigger**;
- GRID infrastructure, software, data processing, DCS system.

Leadership in the physics exploitation:
- Flagship analysis: $K^+ \rightarrow \pi^+ \nu \nu$;
- Detector performance & rare decay studies with 2015+2016 data.
- Analyses of “old” NA48/NA62 data.

Major leadership roles:
- **Physics coordination**: ★
- **Software coordination**;
- **Run coordinators**: 4 out of 15 (in 2016); ★
- **Editorial Board** membership: 3 out of 10;
- **Conference Committee** chair.

★ = new responsibilities
Run 2 and Run 3 programme

- **NA62 Run 2 (2015–2018)** is focused on $K^+ \rightarrow \pi^+ \nu \nu$.
  - Trigger bandwidth for other physics is limited.
  - Several measurements at nominal $\text{SES} \sim 10^{-12}$: $K^+ \rightarrow \pi^+ A', \pi^0 \rightarrow \nu \nu$.
  - A few measurements do not require extreme SES: $K^+ \rightarrow \ell^+ \nu_H$, ...
  - In general, limited sensitivities to rare/forbidden decays ($\text{SES} \sim 10^{-10}$ to $\sim 10^{-11}$, similar to NA48/2 and BNL-E865).
  - A proof of principle for the broad rare/forbidden decay programme.

- **NA62 Run 3 (2021–2024)** programme is under discussion.
  [will be presented at “Physics Beyond Colliders” workshop, CERN, Sep 2016]
  - Existing apparatus, different trigger logic: **no capital investment**.
  - Rare/forbidden $K^+$ and $\pi^0$ decays at $\text{SES} \sim 10^{-12}$:
    - $K^+$ physics: $K^+ \rightarrow \pi^+ \ell^+ \ell^-$, $K^+ \rightarrow \pi^+ \gamma \ell^+ \ell^-$, $K^+ \rightarrow \ell^+ \nu \gamma$, $K^+ \rightarrow \pi^+ \gamma \gamma$, ...
    - $\pi^0$ physics: $\pi^0 \rightarrow e^+ e^-$, $\pi^0 \rightarrow e^+ e^- e^+ e^-$, $\pi^0 \rightarrow 3 \gamma$, $\pi^0 \rightarrow 4 \gamma$, ...
  - Searches for LFV/LNV: $K^+ \rightarrow \pi^- \ell^+ \ell^+$, $K^+ \rightarrow \pi^+ \mu e$, $\pi^0 \rightarrow \mu e$, ...
  - Possibly $K_L$ rare decays ($\text{SES} \sim 10^{-11}$), including $K_L \rightarrow \pi^0 \ell^+ \ell^-$ [CPV].
  - Dump mode: hidden sector searches (long-lived HNL, DP, ALP).
Beyond 2024

- Need to measure both $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ vs $\text{BR}(K_L \rightarrow \pi^0 \nu \nu)$: affected differently by NP.
- In the next few years, we expect:
  - NA62 @ CERN to measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ to 10%.
  - KOTO @ J-PARC to observe a few $K_L \rightarrow \pi^0 \nu \nu$ events.
- A new, possibly multi-purpose, $K_L$ experiment at CERN focussed on $K_L \rightarrow \pi^0 \nu \nu$, with $\text{SES} \sim 0.5 \times 10^{-12}$ is under consideration for Run 4 (2026–2029).

KOTO:

- 30 GeV protons (300 kW); $<p_{KL}> = 2$ GeV/c.
- Proposal: $\text{SES} = 8 \times 10^{-12}$ (~4 SM evts) with $S/B = 1.4$ in three years.
- Short (100h) run in 2013: $\text{SES} = 1.3 \times 10^{-8}$.
- Observed 1 event, expected 0.36; [CKM2014]
- Collected $\times 20$ more data in 2015.
- Intention (no proposal): upgrade to 100 SM evts.

KLEVER @ CERN:

- 400 GeV protons; $<p_{KL}> \sim 100$ GeV/c: complementary approach to KOTO.
- 60 SM events in 5 years with $S/B \approx 1$.
- Protons required: $5 \times 10^{19}$ (NA62 $\times 10$): target area & transfer line upgrade.
- Re-use NA62 infrastructure and parts of detector (LKr calorimeter; muon system).
Recent & upcoming results: 2003-2007 data samples

UK groups have been consistently responsible for >50% of the physics output of the “old” CERN kaon experiments

Recent results:

- Search for lepton number violation and resonances in $K^\pm \rightarrow \pi \mu \mu$ decays [Birmingham & Liverpool]
- Search for dark photon production: $\pi^0 \rightarrow \gamma A'$ [Birmingham]
- $\pi^0$ transition form factor measurement [Birmingham & Bratislava]
- Searches for heavy neutral leptons: $K^+ \rightarrow \ell^+ \nu$ [Birmingham]
\( K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm: \) lepton number violation

- NA48/2 three-track data sample is analyzed.
- Main background: \( K^\pm \rightarrow 3\pi^\pm \) with \( \pi^\pm \rightarrow \mu^\pm \nu \) decays in flight.
- Upper limit on LNV decay + searches for 2-body resonances.
- Proof of principle for NA62 analysis at \( SES \sim 10^{-12} \).

\[ N(\mu^\pm \mu^\pm) = 1 \]
\[ N_{bkg} = 1.16 \pm 0.87 \]
\[ BR(K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} \text{ [90\% CL]} \]

\( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \) candidates

FCNC decay studied earlier: 3.5k candidates

\( PLB697 \text{ (2011)} \) 107

\( K^\pm \rightarrow \pi^\pm \pi^\mp \pi^- \) (also used for normalization)
If the dark photon ($A'$) couples to quarks and decays mainly to SM fermions, it is **ruled out** as the explanation for the anomalous $(g-2)_\mu$.

[NA48/2 collaboration, PLB746 (2015) 178]
**π^0** form factor (2007 data)

**Fit illustration: Data/MC(a=0)**

- **Data / MC(a=0)**
- **Form factor: best fit**
- **Form factor: ±1σ band**

20 equipopulous x bins

χ^2/ndf = 52.5/49, p-value = 0.34

**World data: π^0 TFF slope measurement with π^0_D decays**

- **Geneva-Saclay (1978)**
  - Fischer et al.
  - 30k events

- **Saclay (1989)**
  - Forvieille et al.
  - 32k events

- **SINDRUM I @ PSI (1992)**
  - Meijer Drees et al.
  - 54k events

- **TRIUMF (1992)**
  - Farzanpay et al.
  - 8k events

**NA62 (2016)**

- (preliminary)
- 1M events

**Preliminary result (2016):**

\[ a = (3.70 \pm 0.53)_{\text{stat}} \pm 0.36_{\text{syst}} \times 10^{-2} \]

[final result & paper in preparation]

First observation (5.8σ) of non-zero TFF slope in the time-like momentum transfer region.
HNL searches

**2007 data**: background-limited; sensitive above 300 MeV/c² unlike BNL E949 (decay at rest)

**2015 data**: a wider programme including $K^+ \rightarrow \ell^+\nu_\ell$, $K^+ \rightarrow \ell^+\nu\nu\nu$ and $K^+ \rightarrow \ell^+\nu A'$.

- The $K^+$ flux of 2007 matched in one week;
- ~10 times lower background; wider $m_N$ range.

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**Limits on $|U_{\mu 4}|^2$ from $K^\pm \rightarrow \mu^\pm \nu$ (production searches)**

- KEK (1982)
- E949 (2015)

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**Signal region**: $m_N > 270$ MeV/c²

$K^+ \rightarrow \mu^+ N$ peaks (MC) corresponding to $BR=10^{-4}$

- The $K^+$ flux of 2007 matched in one week;
- ~10 times lower background; wider $m_N$ range.

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... 2015 data

- $\sim 20\times 10^6 K_{\mu 2}$ decays with 1 week of data; $\sim 10^{-5}$ background

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**Summary**

- **UK participation in NA62 from 2011:**
  - Capital funding and manpower for detector construction and operation from ERC Advanced and Royal Society Grants.
  - Soon after, STFC contribution with M&O costs.
  - KTAG detector delivered on time and exceeds specifications.
  - Now in exploitation mode: supported by STFC Particle Grant.
  - Extremely good value for STFC investment (M&O, 1 postdoc, 2 Rutherford fellows, travel, some academic time).
  - Strong UK leadership in physics analysis: both NA62 and “old” data. Recently, UK-led best limits on $K^\pm \rightarrow \pi^\mp \mu^+\mu^-$, $\pi^0 \rightarrow \gamma A'$, HNL; $\pi^0$ TFF.

- **NA62 run 2015–2018:**
  - Running at 20% intensity now, and going to 50% soon.
  - Expect a few SM $K_{\pi\nu\nu}$ events sensitivity by the end of 2016.
  - Focused on the $K_{\pi\nu\nu}$ measurement ($\text{SES} \sim 10^{-12}$).

- **NA62 run 2021–2024:**
  - An extensive $K^+/K_L/\pi^0$ rare decay and beam dump programme with existing detector is being developed.
  - A new $K_L$ experiment afterwards is under consideration.

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Backup
Beam dump mode: HNL decays

\[ D^\pm_{(S)} \rightarrow \ell^\pm N \]
0(10^{15}) decays/year at target

\[ K^\pm \rightarrow \ell^\pm N \]

Search for decays:
- \[ N \rightarrow \pi^\pm \ell^\mp \] (0.14 GeV/c^2 < m_N < 1.9 GeV/c^2)
- \[ N \rightarrow \rho^\pm \ell^\mp \] (0.8 GeV/c^2 < m_N < 1.9 GeV/c^2)

The expected sensitivity is evaluated assuming zero background.

Backgrounds to be considered:
- scattering of halo muons (\( \mu^\pm N \rightarrow K^0 X \)),
- charge exchange in KTAG/GTK (\( K^+ n \rightarrow K^0 p \)),
- accidentals (\( K^+ \) decays, halo muons).

Improvements over the world data are possible also for dark photon and axion production on Be target.

Proof-of-principle: the 2016 data.
Primary beam for both NA62 and SHiP: **400 GeV/c SPS protons**

<table>
<thead>
<tr>
<th></th>
<th>NA62 (running experiment)</th>
<th>SHiP (proposal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years of operation</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>POT per SPS spill</td>
<td>$3 \times 10^{12}$</td>
<td>$4 \times 10^{13}$</td>
</tr>
<tr>
<td>POT total</td>
<td>$5 \times 10^{18}$</td>
<td>$2 \times 10^{20}$</td>
</tr>
<tr>
<td>Decay volume (m$^3$)</td>
<td>260 m$^3$</td>
<td>1780 m$^3$</td>
</tr>
<tr>
<td>Decay volume distance to target</td>
<td>104–183 m</td>
<td>64–124 m</td>
</tr>
<tr>
<td>Decay volume pressure (bar)</td>
<td>$10^{-9}$ bar</td>
<td>$10^{-6}$ bar</td>
</tr>
<tr>
<td>Halo muon rate in spectrometer</td>
<td>6 MHz</td>
<td>few kHz</td>
</tr>
<tr>
<td>Straw chamber area</td>
<td>$0.06m &lt; R &lt; 1.05m$</td>
<td>$R_1 = 5m$, $R_2 = 10m$</td>
</tr>
</tbody>
</table>

... but a crucial aspect is the background rejection capability!
LFV in $K^\pm$ and $\pi^0$ decays

<table>
<thead>
<tr>
<th>Mode</th>
<th>UL at 90% CL</th>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu^+ e^-$</td>
<td>$1.3 \times 10^{-11}$</td>
<td>BNL E777/E865</td>
<td>PRD 72 (2005) 012005</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu^- e^+$</td>
<td>$5.2 \times 10^{-10}$</td>
<td>BNL E865*</td>
<td>PRL 85 (2000) 2877</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^- \mu^+ e^+$</td>
<td>$5.0 \times 10^{-10}$</td>
<td>BNL E865*</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^- e^+ e^+$</td>
<td>$6.4 \times 10^{-10}$</td>
<td><strong>CERN NA48/2</strong></td>
<td>PLB 697 (2011) 107</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu^- e^+$</td>
<td>$1.1 \times 10^{-9}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^- \nu e^+ e^+$</td>
<td>$2.0 \times 10^{-8}$</td>
<td>Geneva-Saclay</td>
<td>PL 62B (1976) 485</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^- \nu \mu^+ e^+$</td>
<td>no data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \mu^+ e^-$</td>
<td>$3.6 \times 10^{-10}$</td>
<td>FNAL KTeV</td>
<td>PRL 100 (2008) 131803</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \mu^- e^+$</td>
<td>$3.6 \times 10^{-10}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* CERN NA48/2 sensitivities for these three modes are similar to those of BNL E865

Expected NA62 single event sensitivities:

$\sim 10^{-12}$ for $K^\pm$ decays, $\sim 10^{-11}$ for $\pi^0$ decays.

- NA62 is capable of improving on all these decay modes.
- Sensitivity will depend on the trigger selectivity.
Interpretation in terms of production and decay of either Majorana neutrino ($N$) or LN conserving heavy neutrino. 
A scan in the parameter space: $m_N$ and $\tau_N$.
Limits of $\sim 10^{-10}$ ($\sim 10^{-9}$) set for $\tau_N < 100$ ps for LNV (LNC) case.
Also background limited; $\text{UL} \sim 10^{-9}$.

This leads to non-trivial limitations on the inflation ($\chi$) phase space: $\chi \rightarrow \mu^+ \mu^-$ decay dominates at $m_\chi \sim 300 \text{ MeV/c}^2$.