Kaon physics experiments

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Outline:
1) $K^+ \rightarrow \pi^+ \nu\nu$ and $K_L \rightarrow \pi^0 \nu\nu$ measurements at NA62 and KOTO.
2) Rare and forbidden kaon decays at NA62.
3) Kaon and hyperon physics at LHCb.
4) The KLEVER initiative at CERN: $K_L \rightarrow \pi^0 \nu\nu$ measurement.

UK input to EPPSU meeting
IPPP Durham • 17 April 2018
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 is 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>$\text{BR}_{\text{SM}} \times 10^{11}$</th>
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<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma)$</td>
<td>$8.4 \pm 1.0$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>$3.4 \pm 0.6$</td>
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The uncertainties are largely parametric (CKM)

_Theoretically clean, almost unexplored, sensitive to new physics._
It is essential to measure both $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$ decays.

Kaon physics alone can fully constrain the unitarity triangle.

Comparison with B physics can provide description of NP flavour dynamics.
Technique: $K^+$ decay at rest

Separated $K^+$ beam (710 MeV/c, 1.6 MHz).
PID: range (entire $\pi^+\rightarrow\mu^+\rightarrow e^+$ decay chain).
Hermetic photon veto system.

Observed candidates: 7
Expected background: 2.6
Final result:

$$BR = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Background is mainly in Region 2, due to $K_{2\pi}$ decay with $\pi^+$ scattering in the target.

Main goal: an improved $K^+ \rightarrow \pi^+ \nu \nu$ measurement with a novel decay-in-flight technique.

Major UK contribution: 11% of the collaboration.
Pion momentum $15 \text{ GeV}/c < p < 35 \text{ GeV}/c$: missing energy of at least $40 \text{ GeV}$.

Hermetic photon veto: $\pi^0 \rightarrow \gamma\gamma$ decay suppression = $3 \times 10^{-8}$.

Particle ID (RICH+LKr+HAC+MUV): muon suppression = $1 \times 10^{-8}$.

Kinematic rejection factors (limited by beam pileup & MCS tails):
1. $1 \times 10^{-3}$ for $K^+ \rightarrow \pi^+\pi^0$,
2. $3 \times 10^{-4}$ for $K \rightarrow \mu^+\nu$. 

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: $400 \text{ GeV}$, $3.3 \times 10^{12}$/spill.
$K^+$: $75 \text{ GeV}/c$ ($\pm 1\%$), divergence < $100 \mu\text{rad}$. Nominal beam rate: 750 MHz, $K^+$ rate 45 MHz; ~5 MHz $K^+$ decays in fiducial volume.
**NA62 physics programme**

- **NA62 Run in 2016–2018:** data collection in progress.
  - Optimized for $K^+ \to \pi^+ \nu\nu$; not a multi-purpose $K^+$ decay experiment.
  - Several searches at nominal $\text{SES} \approx 10^{-12}$: $K^+ \to \pi^+ A', \pi^0 \to \nu\nu$.
  - A limited number of rare decays to be measured:
    - world’s largest samples of $K^+ \to \pi^+ \mu^+\mu^-$, $K^+ \to \ell^+\gamma\gamma$, $K^+ \to \pi^+\gamma\gamma$.
  - Lepton universality test: $R_K = \frac{\text{BR}(K^+ \to e^+\nu)}{\text{BR}(K^+ \to \mu^+\nu)}$.
  - LNV/LFV searches at $\sim 10^{-11}$ level: $K^+ \to \pi^-\ell^+\ell^+$, $K^+ \to \pi^+\mu\nu$, $\pi^0 \to \mu\nu$, ...
  - Searches for heavy neutral lepton production: $K^+ \to \ell^+ N$.
  - Searches for long-lived ($O(1\text{ns})$) light particles, e.g. $K^+ \to \pi^+ S$, $S \to \mu^+\mu^-$.

- **NA62 Run in 2021–2023:** part of Physics Beyond Colliders study at CERN
  - Existing apparatus: **no capital investment**.
  - Further $K^+ \to \pi^+\nu\nu$ data collection to reach 100 SM events.
  - Beam dump operation with $10^{18}$ pot (=3 months of data taking): competitive searches for hidden sector (long-lived HNL, DP, ALP).
  - Trigger improvements foreseen for forbidden decays.
NA62 data collection

- Commissioning run 2015: minimum bias (~1% of nominal beam intensity). Most systems commissioned and meet the design requirements.
- Physics run 2016 (40% intensity, limited by beam quality): $1.2 \times 10^{11}$ $K^+$ useful decays (1 month) for $K^+ \rightarrow \pi^+ \nu\nu$ analysis; analysis completed
- Physics run 2017 (65% intensity): $\sim 3 \times 10^{12}$ useful $K^+$ decays.
- Physics run 2018 started last week: 218 days scheduled.
Main $K^+$ decay modes (>90% of BR) rejected kinematically.

Design kinematical resolution on $m_{\text{miss}}^2$ has been achieved ($\sigma=1.0\times10^{-3}$ GeV$^4$/c$^2$).

Measured kinematical background suppression:
- $K^+\rightarrow\pi^+\pi^0$: $1\times10^{-3}$;
- $K^+\rightarrow\mu^+\nu$: $3\times10^{-4}$.

Further background suppression:
- PID (calorimeters & Cherenkov detectors): $\mu$ suppression $10^{-8}$.
- Hermetic photon veto: suppression of $\pi^0\rightarrow\gamma\gamma$ decays $3\times10^{-8}$. 

$K_{\pi\nu\nu}$ signal region definition

$\mathbf{m}_{\text{miss}}^2=(P_K-P_\pi)^2$ vs track momentum

$K^+\rightarrow\pi^+\pi^+\pi^-$
$K^+\rightarrow\pi^+\pi^0\pi^0$

Region I

Region II
Data sample: one month at 40% of nominal intensity.

Number of kaon decays: $N_K = (1.21 \pm 0.02_{\text{syst}}) \times 10^{11}$.

The analysis procedure is fully established.

Background estimates are mostly data-driven.

Signal acceptance: $A_{\pi\nu\nu} = (4.0 \pm 0.1\%)$.

Single-event sensitivity: $\text{SES} = (3.15 \pm 0.24) \times 10^{-10}$.
One $K^+ \rightarrow \pi^+ \nu \nu$ candidate observed: $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) < 11 \times 10^{-10}$ at 90% CL.

BNL 949 ($K^+$ decay at rest): $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

SM prediction: $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) = (0.84 \pm 0.10) \times 10^{-10}$

- The NA62 decay-in-flight technique works.
- Non-trivial result with $\sim 1\%$ of the total statistics foreseen.
- Improved beamline shielding in 2017: improved acceptance/background.
Protons of $30 \text{ GeV/c}$, $16^\circ$ production angle: $K_L$ spectrum peaks at $1.4 \text{ GeV/c}$.

- Beam composition: $K_L$, neutrons, photons.
- Fiducial decay region length: $3 \text{ m}$.
- CsI calorimeter + hermetic veto.
- In 2013, $3 \times 10^{13}$ pot per $2 \text{ s}$ pulse (25 kW).
- Higher intensity in 2015/16: $30/42 \text{ kW}$.
- Analysis of 2013 data is complete; 2015/16 sample is ~20 times larger.
KOTO: result with 2013 data.

[PTEP 2017, 021C01]

Result with 2013 data:

- About 100h of data; SES = 1.3×10^{-8}.
- Background dominated by halo neutrons.
- Signal acceptance = 1.02%.
- One event observed, with an expected background of 0.34±0.16.
- BR(K_L→π^0νν)<5.1×10^{-8} at 90% CL.
- The strongest limit is still 2.6×10^{-8}.

[KEK E391a, PRD81 (2010) 072004]

Principal backgrounds:

- (0.18±0.15) Neutron directly hit on CsI
- (0.056±0.056) Pion produced at detector upstream

Also, K_L→π^0π^0 and K_L→γγ backgrounds

Improvements in 2015/16:

- Better photon-neutron ID in calorimeter (cluster+pulse shape).
- Thinner vacuum window: reduction of π^0 production by neutrons.
- SES with the 2015/16 sample <10^{-9}.
- Further upgrades are in progress.
- SM sensitivity (~10^{-11}) by 2021.
**K→πνν: prospects**

**KOTO 2015/16 result:** in 2018?

**KOTO upgrade:** SM sensitivity after 2021

**NA62 (2016–18 data):**
- ~20 SM events by 2020
- ~100 SM events by 2025?
About 30% of the 2016+2017 data set: $6.3 \times 10^{11}$ $K^+$ decays.

World’s largest $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ sample: 4.6k events.

Expect a competitive $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ measurement with $\sim 10k$ events: LU test.

Search for $K^+ \rightarrow \pi^- \mu^+ \mu^+$ is not limited by background; $\text{SES}=2 \times 10^{-11}$.

Search for $K^+ \rightarrow \pi^+ X$, $X \rightarrow \mu^+ \mu^-$: $\text{SES} \sim 10^{-10}$ for lifetimes up to $O(1 \text{ ns})$. 

E. Goudzovski / IPPP Durham, 17 April 2018
Dedicated (downscaled) 3-track trigger lines are in operation.

About 30% of the 2016+2017 data set: $1.3 \times 10^{11}$ $K^+$ decays.

For $m_{ee} > 140$ MeV/$c^2$, background-free $K^+ \rightarrow \pi^+ e^+ e^-$ sample, 1.1k events.

First observation of $K^+ \rightarrow \pi^+ e^+ e^-$ in the region $m_{ee} < 140$ MeV/$c^2$.

Search for $K^+ \rightarrow \pi^- e^+ e^+$ is not limited by background; SES = $2 \times 10^{-10}$.

Search for $K^+ \rightarrow \pi^+ X$, $X \rightarrow e^+ e^-$, $10 < m_X < 100$ MeV/$c^2$: SES ~ $10^{-9}$ for lifetime $\ll 1$ ns.
NA62: $K^+ \rightarrow \ell^+ N$ (2015 data)

- Minimum bias data (1% intensity); 12k spills (5 days).
- Numbers of $K^+$ decays in fiducial volume:
  \[ N_K = (3.01 \pm 0.11) \times 10^8 \] in positron case; \[ N_K = (1.06 \pm 0.12) \times 10^8 \] in muon case.
- Beam tracker not available: kaon momentum is estimated as the beam average.
- HNL production signal: a spike above continuous missing mass spectrum.

Beam tracker not available: kaon momentum is estimated as the beam average.

HNL production signal: a spike above continuous missing mass spectrum.

Squared missing mass: $(P_{K} - P_{e})^2$

$K^+ \rightarrow e^+ \nu$,
BR=1.6×10^{-5}: 1.7k candidates

$K^+ \rightarrow \mu^+ \nu$, BR=64%: 24M candidates

HNL search region: low background due to photon veto and kaon ID

HNL search region
NA62 limits on HNL production

Upper limits on BR(K⁺→ℓ⁺N)

|U_{\ell 4}|^2 limits from production searches

- Reached $10^{-6}$–$10^{-7}$ limits for $|U_{\ell 4}|^2$ in the 170–448 MeV/c^2 mass range; improvement on the world data in 5 days and without the beam tracker.
- Estimated sensitivity with the full sample: $\sim 10^{-9}$ for $|U_{e 4}|^2$, $\sim 10^{-8}$ for $|U_{\mu 4}|^2$.

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K_s physics at LHCb

- A new upper limit on $K_s \rightarrow \mu^+\mu^-$ with 3 fb$^{-1}$: [EPJC 77 (2017) 678]

$$\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) < 0.8(1.0) \times 10^{-9} \text{ at } 90(95)\% \text{ of CL}$$

Ultimate LHCb sensitivity: down to $10^{-11}$.

SM prediction: $\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$

- A sensitivity study performed for $K_s \rightarrow \pi^0\mu^+\mu^-$. Prospects to improve over NA48/1 measurement:

$$\mathcal{B}(K^0_S \rightarrow \pi^0\mu^+\mu^-) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$$

[PLB599 (2004) 197]

- A sensitivity study performed for $K_s \rightarrow \pi^+\pi^-e^+e^-$. Potentially competitive with NA48 measurements (23k events)

$$\mathcal{B}(K^0_S \rightarrow \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$$

[EPJ C30 (2003) 33; PLB694 (2011) 301]

- Possibly first searches for $K_s \rightarrow \ell^+\ell^-\ell^+\ell^-$ (SM BRs below $10^{-10}$)?

(More details: talks by F. Dettori and M. Ramos Pernas at RKF workshop, Feb 2018)
LHCb: evidence for $\Sigma^+ \rightarrow p\mu^+\mu^-$

- A rare FCNF decay: $1.6 \times 10^{-8} < \text{BR}_{\text{SM}} < 9.0 \times 10^{-8}$.
- HyperCP anomaly: 3 candidates, all with $m(\mu^+\mu^-) \approx 214 \text{ MeV/c}^2$.
- LHCb analysis: full 2011+12 sample, 3 fb$^{-1}$.

**Decay rate measurement:**

$$\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = \left(2.1^{+1.6}_{-1.2}\right) \times 10^{-8}$$

- Consistent with SM prediction; no evidence for the HyperCP resonance.
- A precision measurement is foreseen with Run II data.
- Proposals to measure baryon dipole moments ($\text{arXiv:1612.06769, 1708.08483}$) and to study semileptonic baryon decays.
A new \( K_L \rightarrow \pi^0 \nu \nu \) experiment at CERN with \( \text{SES} \sim 0.5 \times 10^{-12} \) (i.e. 60 SM events) and \( S/B \sim 1 \) with 5 years of data taking is under consideration for 2026 +.

- Mean \( K_L \) momentum of 97 GeV/c: easier photon veto wrt KOTO.
- Longer \( K_L \) lifetime, tight collimation: need \( 5 \times 10^{19} \) pot/year (6x NA62 intensity).
- Target area and transfer line upgrade is under study.
- Re-use NA62 infrastructure and possibly parts of detector (LKr, HAC).
- Possibly add a tracking system? Then \( K_L \rightarrow \pi^0 \ell^+ \ell^- \) (\( \text{BR}_{\text{SM}} \sim 10^{-11} \)) are accessible.

Project represented at CERN Physics Beyond Collider study; expression of interest to CERN SPSC in preparation.

E. Goudzovski / IPPP Durham, 17 April 2018
Active kaon experiments; **NA62@CERN, KOTO@J-PARC, LHCb@CERN.** UK makes major contributions to the CERN kaon experiments.

- **By 2020,** expect major improvement of the experimental information on $K^+ \rightarrow \pi^+ \nu\nu$ and $K_L \rightarrow \pi^0 \nu\nu$. Also, the ultimate sensitivity of the NA62 method will be understood.

- **By 2025,** expect a $K^+ \rightarrow \pi^+ \nu\nu$ measurement to 10% precision (NA62) and the first evidence for $K_L \rightarrow \pi^0 \nu\nu$ (KOTO).

- On the same time scale, expect many new NA62/LHCb results on rare/forbidden kaon decays, lepton universality, LF/LN conservation tests, HNL production, etc.

- **After 2025:** a dedicated $K_L \rightarrow \pi^0 \nu\nu$ experiment at CERN to collect 60 SM events with $S/B \sim 1$ in 5 years?