Kaon experiments at CERN: recent results & prospects

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Outline:
1) $K^\pm$ decay experiments at CERN: NA48/2, NA62-$R_K$, NA62
2) NA62 status and data quality
3) Recent results from Birmingham-led analyses
4) Conclusions
Discovery of a Higgs boson: success of the Standard Model (SM)

No roadmap and “guaranteed discoveries” any longer: a data-driven era

Limitations of the SM:
SM matter $\approx 5\%$ of total mass-energy

“New physics” extensions:
undiscovered particles

Searches for New physics: two complementary approaches

Energy frontier (LHC)
Direct production of new particles in high-energy collisions.

A unique effort

Precision (intensity) frontier
Low-energy observables:
tests of precise SM predictions for rare or forbidden processes.

A collective effort
The precision frontier: kaon physics

The kaon:

- One of the lightest unstable particles (discovered in 1947); the “minimal flavour laboratory”.
- High production rates: high statistical precision. An example of rare K decay measurement: \( \text{BR}(K_L \rightarrow e^+e^-) = (9\pm5)\times10^{-12}. \) (BNL E871)
- Essential in establishing the foundations of particle physics (quark mixing, CPV).
- Current focus: searches for new physics with rare and forbidden decays.

Tree-level process: \( \frac{\Gamma_X}{\Gamma_{\text{SM}}} \sim \left( \frac{g_X}{g_W} \cdot \frac{M_W}{M_X} \right)^4 \)

For \( g_X \approx g_W \) and \( \beta \sim 10^{-12} \), \( M_X \sim 100 \text{ TeV} \)

Example: \( K_L \rightarrow \mu^+e^- \)
Kaon physics facilities

BNL
E865, E777, E787, E949

CERN
NA48, NA62, LHCb

IHEP Protvino
ISTRA+, OKA, KLOD

FNAL
KTeV

LNF
KLOE, KLOE-2

KEK/J-PARC
E391a, KOTO, TREK

A variety of experimental techniques:
\( K \) decay-in-flight (e.g. at CERN), stopped \( K^+ \), \( \phi \) factory

E. Goudzovski / Birmingham, 2 November 2016
Kaon experiments at CERN
Kaon programme at CERN

Kaon decay in flight experiments.
NA62: currently ~200 participants, ~30 institutions

Earlier: NA31

1997: \(\varepsilon'/\varepsilon: K_L+K_S\)
1998: \(K_L+K_S\)
1999: \(K_L+K_S\) \(K_S\) HI
2000: \(K_L\) only \(K_S\) HI
2001: \(K_L+K_S\) \(K_S\) HI
2002: \(K_S/\)hyperons
2003: \(K^+/K^-\)
2004: \(K^+/K^-\)
2007: \(K^\pm_{e2}/K^\pm_{\mu2}\) tests
2008: \(K^\pm_{e2}/K^\pm_{\mu2}\) tests
2014: pilot run
2015--: data taking
# K± decay experiments at CERN

## Experiment

<table>
<thead>
<tr>
<th></th>
<th>NA48/2 (K±)</th>
<th>NA62 (R_K phase) (K±)</th>
<th>NA62 (K+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum, GeV/c</td>
<td>60</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td>RMS momentum bite, GeV/c</td>
<td>2.2</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Spectrometer thickness, X₀₀</td>
<td>2.8%</td>
<td>2.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Spectrometer P_T kick, MeV/c</td>
<td>120</td>
<td>265</td>
<td>270</td>
</tr>
<tr>
<td>M(K±→π±π⁺π⁻) resolution, MeV/c²</td>
<td>1.7</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>K decays in fiducial volume</td>
<td>2×10¹¹</td>
<td>2×10¹⁰</td>
<td>1.2×10¹³</td>
</tr>
<tr>
<td>Main trigger</td>
<td>multi-track; K±→π⁺π⁻π⁰π⁰ + e±</td>
<td>Min.bias + K_{πνν} + ...</td>
<td></td>
</tr>
</tbody>
</table>

## The NA62 experiment

- **Main goal:** collect 100 SM K⁺→π⁺νν decays, BR_{SM} = (9.11±0.72)×10⁻¹¹. *Buras et al.,* JHEP 1511 (2015) 033
- **Current K⁺→π⁺νν experimental status:** BR = (1.73^{+1.15}_{−1.05})×10⁻¹⁰ from 7 candidates with expected background of 2.6 observed by BNL-E949. *PRL101 (2008) 191802*

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NA48/2 and NA62-\(R_K\) experiments

2003–2007: charged kaon beams, the NA48 detector

Narrow momentum band \(K^\pm\) beams:
\[ P_K = 60 (74) \text{ GeV/c}, \delta P_K / P_K \sim 1\% \text{ (rms)}. \]

- Maximum \(K^\pm\) decay rate \(~100 \text{ kHz}\);
- **NA48/2**: six months in 2003–04;
- **NA62-\(R_K\)**: four months in 2007.

Principal subdetectors:

- **Magnetic spectrometer (4 DCHs)**
  4 views/DCH: redundancy \(\Rightarrow\) efficiency;
  \[ \delta p / p = 0.48\% \oplus 0.009\% p \text{ [GeV/c]} \text{ (in 2007)} \]

- **Scintillator hodoscope (HOD)**
  Fast trigger, time measurement (150ps).

- **Liquid Krypton EM calorimeter (LKr)**
  High granularity, quasi-homogeneous;
  \[ \sigma_E / E = 3.2\% / E^{1/2} \oplus 9\% / E \oplus 0.42\% \text{ [GeV]}; \]
  \[ \sigma_x = \sigma_y = 4.2 \text{ mm} / E^{1/2} \oplus 0.6 \text{ mm} \text{ (1.5 mm@10 GeV)}. \]
The NA62 experiment

Un-separated hadron (p/π+/K+) beam. 400GeV SPS protons (10^{12}/spill); K+: 75GeV/c (±1%), divergence < 100μrad. 800MHz beam rate → 45MHz K+ rate → 5MHz K+ decays in fiducial volume.

- Expected single event sensitivities: ~10^{-12} for K± decays, ~10^{-11} for π^0 decays.
- Kinematic rejection factors (limited by beam pileup and tails of MCS): 5×10^3 for K^+→π^+π^0, 1.5×10^4 for K→μ^+ν.
- Hermetic photon veto: ~10^8 suppression of π^0→γγ.
- Particle ID (RICH+LKr+MUV): ~10^7 muon suppression.

Total length: ~270m
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

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\text{BR}_{\text{SM}} \times 10^{11}$</th>
</tr>
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<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.
**K → πνν̅: experiment vs theory**

**NA62 aim:** collect \( O(100) \) SM \( K^+ → π^+νν̅ \) decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

**Signature:** high momentum \( K^+ \) (75 GeV/c) → low momentum \( π^+ \) (15–35 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) → high rates, additional background sources.
NA62 physics programme

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

- **NA62 Run 3 (2021–2024)**: programme is under discussion.
  
  [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: $K^+ \to \pi^+ \ell^+ \ell^-$, $K^+ \to \pi^+ \gamma \ell^+ \ell^-$, $K^+ \to \ell^+ \nu \gamma$, $K^+ \to \pi^+ \gamma \gamma$, ...
    - $\pi^0$ physics: $\pi^0 \to e^+ e^-$, $\pi^0 \to e^+ e^- e^+ e^-$, $\pi^0 \to 3 \gamma$, $\pi^0 \to 4 \gamma$, ...
    - Searches for LFV/LNV: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, ...
  - Possibly $K_L$ rare decays ($\text{SES} \sim 10^{-11}$), including $K_L \to \pi^0 \ell^+ \ell^-$ [CPV].
  - Dump mode: hidden sector searches (long-lived HNL, DP, ALP).
The lepton programme

Neutrino oscillations discovery (1998)

Neutrino source  Neutrino detector

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

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

- Birmingham-led programme (supported by ERC starting grant): search for forbidden states with lepton pair (ee, μμ, μe)

\[
\begin{align*}
K^+ &\to \pi^+ \mu^+ e^- \\
K^+ &\to \pi^+ \mu^- e^+ \\
K^+ &\to \pi^- \mu^+ e^+ \\
K^+ &\to \pi^- e^+ e^+ \\
K^+ &\to \pi^- \mu^+ \mu^+ \\
K^+ &\to \mu^- \nu e^+ e^+ \\
K^+ &\to e^- \nu \mu^+ \mu^+ \\
K^+ &\to \pi^+ \pi^0, \quad \pi^0 \to \mu^+ e^- \\
K^+ &\to \pi^+ \pi^0, \quad \pi^0 \to \mu^- e^+
\end{align*}
\]
NA62 status & data quality
Data collection

- Minimum bias (~1% intensity) and $K_{\pi\nu\nu}$ test data collected in 2015
  - Most systems commissioned and meet the design requirements
- Beam time in 2016: 3 May – 14 November.
  - running at ~35% of the nominal intensity now (limited by SPS capability)
- Long (~6 months) runs scheduled in 2017 and 2018.

Expect to reach a few SM $K_{\pi\nu\nu}$ events sensitivity with 2016 data

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ signal (2016)

Rare decay: $BR \sim 10^{-7}$
92% of total $\text{BR}(K^+)$:

- Outside the signal kinematic region.
- Signal region is split into Region I and Region II by the $K^+ \rightarrow \pi^+\pi^0$ peak.

8% of total $\text{BR}(K^+)$ including multi-body:

- Span across the signal region (not rejected by kinematic criteria).
- Rejection relies on hermetic photon system, PID, sub-ns timing.
Kinematics: 2015 data

\[ m_{\text{miss}}^2 = (P_K - P_\pi)^2 \text{ vs } p_\pi \]

Kaon decays (KTAG signal)

- Gigatracker information not used in this study.
- Photon veto criteria not applied on purpose.
- Kinematic & time resolutions are close to the design.

\[ K^+ \rightarrow \pi^+ \pi^+ \]
\[ K^+ \rightarrow \pi^0 \ell^+\nu \]
\[ K^+ \rightarrow \mu^+\nu \]
\[ K^+ \rightarrow 3\pi \]

Hadron beam (75 GeV)

Beam halo

\[ \pi^+ \rightarrow \mu^+\nu \text{ threshold at 75 GeV/c} \]

Beam activity (no KTAG signal)

\[ m_{\text{miss}}^2 \text{ vs } P_\pi \text{ (GeV/c)} \]

K\(_{\pi\nu\nu}\) region II

K\(_{\pi\nu\nu}\) region I

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Kaon identification: KTAG

NA62UK; 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:
σ(K time) = 70ps

scattering in 1st dynode

Working point:
5-fold coincidence

95%

Kaon ID efficiency vs sectors in coincidence

E. Goudzovski / Birmingham, 2 November 2016
- Three Si pixel stations on the beam.
- Operation at beam rates up to 800 MHz.
- In total, 54k pixels (300×300 μm²).
- Thickness: <0.5% $X_0$ per station.
- Cooling using microchannel technique.
- On-sensor TDC readout chip.
- Measured performances match the design. $\sigma(t_{\text{BeamTrack}}) \approx 200$ ps.
PID technique: RICH, EM & hadronic calorimeters.

Goal: $O(10^7)$ muon mis-ID suppression to reduce $K^+ \rightarrow \mu^+\nu$ background to $K^+ \rightarrow \pi^+\nu\nu$.

RICH provides optimal $\mu/\pi$ separation at $15 \text{ GeV/c} < p < 35 \text{ GeV/c}$: measured $\mu$ suppression $\approx 10^2$ at $\pi$ ID efficiency of $\sim 90\%$.

Calorimeters: EM (LKr), hadronic (MUV1+MUV2); additional $(10^4 \div 10^6)$ $\mu$ suppression at $(90\% \div 40\%)$ $\pi^+$ ID efficiency.
Technique: EM calorimetry exploiting correlations between photons from $\pi^0 \rightarrow \gamma \gamma$ decays.

Goal: $O(10^8)$ rejection of $\pi^0$ from $K^+ \rightarrow \pi^+ \pi^0$ decays.

Signal region: $p(\pi^+)<35$ GeV/c, therefore $p(\pi^0)>40$ GeV/c.

Rejection factor measured with 2015 data from $K^+ \rightarrow \pi^+ \pi^0$ decays: $O(10^6)$ rejection achieved; analysis of large 2016 sample on-going.
Birmingham-led analyses

The Birmingham NA62 group has produced >50% of the physics output of the “old” CERN $K^\pm$ experiments

Recent results with 2003–2007 data:

- Search for lepton number violation and resonances in $K^\pm \rightarrow \pi \mu \mu$ decays [presented at 2016 conferences; to be published in early 2017]
- $\pi^0$ transition form factor measurement [presented at 2016 conferences; to be published in early 2017]
- Search for dark photon production: $\pi^0 \rightarrow \gamma A'$ [published in 2015]

Near-future prospects:

- Searches for heavy neutral leptons: $K^+ \rightarrow \ell^+ \nu_H$ [expect to presented at the 2017 winter conferences]
$K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$: lepton number violation

- NA48/2 data sample. $K^\pm \rightarrow \pi \mu \mu$ selection: 3-track vertex; no missing momentum; muon ID (LKr, muon detector).
- Blind analysis: selection optimized with dedicated MC samples.
- Main background: $K^\pm \rightarrow 3\pi^\pm$ with $\pi^\pm \rightarrow \mu^\pm \nu$ decays in flight.
- Muon identification optimized for background reduction.

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

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Interpretation of the LNV result in terms of Majorana neutrino ($N$) production and decay. [Atre et al, JHEP 0905 (2009) 030]

A scan in the parameter space: $m_N$ and $\tau_N$.

Due to the 3-track vertex selection constraint, acceptance falls as $\sim 1/\tau_N$ for $\tau_N > 1$ ns.

Limits of $\sim 10^{-10}$ set for $\tau_N < 100$ ps.
Search for $K^\pm \rightarrow \mu^\pm N$, $N \rightarrow \pi^\pm \mu^\mp$

- Search for LN conserving heavy neutrino production and decay.
- Sensitivity limited by background from the FCNC $K^\pm \rightarrow \pi^\pm \mu^+\mu^-$ decay.
- Limits of $\sim 10^{-9}$ set for $\tau_N < 100$ ps.

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Search for $K^\pm \rightarrow \pi^\pm X$, $X \rightarrow \mu^+\mu^-$

- 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 $m_\chi \sim 300$ MeV/c$^2$.

$\pi^0$ physics: $\pi^0$ transition form factor; search for dark photon ($\pi^0 \rightarrow \gamma A'$)
NA62-R_K: $\pi^0_D \rightarrow \gamma e^+e^-$ sample

- NA62-R_K data: $\sim 2 \times 10^{10}$ $K^\pm$ decays in the fiducial decay region.
- Reconstructed $\pi^0_D$ decay candidates, $x = (m_{ee}/m_\pi)^2 > 0.01$: $N(K_{2\pi D}) = 1.05 \times 10^6$.
- Despite $\sim 10$ times smaller sample wrt NA48/2, good for spectrum study:
  - minimum bias trigger: low systematics due to trigger efficiency;
  - low beam intensity: low systematics due to accidentals.
- Source of $\pi^0$ considered: $K^\pm \rightarrow \pi^\pm \pi^0$ decay (BR=20.7%).

![Graphs showing NA62 mass and Dalitz plots](image-url)
TFF slope measurement: result

**NA62-R_K preliminary result (2016):**
\[
a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2}
\]
*final result & paper in preparation*

**World data: \(\pi^0\) TFF slope measurement with \(\pi^0_D\) decays**

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

- **Saclay (1989)**
  - Fonvieille 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

**First observation** (5.8\(\sigma\)) of **non-zero TFF slope** in the time-like momentum transfer region.

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Two exclusive selections

\( K^\pm \rightarrow \pi^\pm \pi^0_D \) selection:
- \(|m_{\gamma ee} - m_K| < 20 \text{ MeV}/c^2\);
- \(|m_{\gamma ee} - m_{\pi 0}| < 8 \text{ MeV}/c^2\);
- no missing momentum.

\( K^\pm \rightarrow \pi^0_D \mu^\pm \nu \) selection:
- \( m_{\text{miss}}^2 = (P_K - P_\mu - P_{\pi 0})^2 \) compatible with zero;
- \(|m_{\gamma ee} - m_{\pi 0}| < 8 \text{ MeV}/c^2\);
- missing total and transverse momentum.

Reconstructed \( \pi^0_D \) decay candidates:
- \( N(K_{\pi 2D}) = 1.38 \times 10^7 \),
- \( N(K_{\mu 3D}) = 0.31 \times 10^7 \),
- total = \( 1.69 \times 10^7 \).

\( K^\pm \) decays in fiducial region:
\( N_K = (1.57 \pm 0.05) \times 10^{11} \).
NA48/2: search for DP signal

UL on the number of DP candidates

UL on BR($\pi^0 \rightarrow \gamma A'$) at 90% CL

- Local signal significance never exceeds $3\sigma$: no DP signal observed.
- The obtained limits are background limited: 2–3 orders of magnitude above single event sensitivity.

DP mass scan:
- range: $9\text{ MeV/c}^2 \leq m_{A'} < 120\text{ MeV/c}^2$;
- mass step $0.5\sigma_m$, signal window $\pm 1.5\sigma_m$;
- DP mass hypotheses tested: 404;
- global fit for the background shape.
● Improvement on the existing limits in the $m_{A'}$ range $9–70$ MeV/c$^2$.

● Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak).

● Sensitivity limited by irreducible $\pi^0_D$ background: upper limit on $\varepsilon^2$ scales as $\sim (1/N_K)^{1/2}$, modest improvement with larger data samples.

● If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous $(g-2)_\mu$.

● Sensitivity to smaller $\varepsilon^2$ with displaced vertex analysis: to be investigated.
Heavy neutral leptons
Constraints on the $\nu$MSM

Neutrino minimal SM ($\nu$MSM) = $SM + 3$ right-handed neutral heavy leptons. [Asaka et al., PLB 631 (2005) 151]

Masses: $m_1 \sim 10$ keV [DM candidate]; $m_{2,3} \sim 1$ GeV. HNLs observable via production and decay.

HNL production, kinematic factor:

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

Asaka et al., PLB 631 (2005) 151

Masses:

- $m_1 \sim 10$ keV [DM candidate]; $m_{2,3} \sim 1$ GeV

HNLs observable via production and decay.

$|U_{l4}|^2$

Astrophysical & cosmological constraints on $m_1, m_{2,3}$

- X-ray constraints $\tau > 10^{24}$ s

$R(m_N)$: R. Shrock

PLB96(1980)159

$m_1$ [keV]

$m_{2,3}$ [GeV]

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Global limits on $|U_{e4}|^2$ vs $m_4$

In contrast to decay searches (e.g. $N \rightarrow \pi l$ at beam dump expt’s), production search results are model-independent.

Global limits on $|U_{\mu4}|^2$ vs $m_4$

Assuming LN conservation, rather weak!

Model-dependent HNL decay searches not considered

[De Gouvêa and Kobach, PRD93 (2016) 033005]
HNL: status of production searches

Peak search for $K^+ \rightarrow \mu^+N$ at NA62-R$_K$ (2007 data):
- Three months of data with downscaled trigger: $\sim 10^8 K^+$ decays in fiducial volume.
- Background-limited; sensitive above $m_N = 300$ MeV/c$^2$ unlike BNL E949 (decay at rest).

Peak search for $K^+ \rightarrow \mu^+N$ at NA62 (2015 data):
- Integrated 2007 $K^+$ flux reached with 1 week of minimum bias data in 2015;
- Low background (hermetic veto, $K^+$ tagger); search region extends into lower $m_N$;
- Excellent conditions to a search for $K^+ \rightarrow e^+N$.

NA62-R$_K$ (2007): $K^+ \rightarrow \mu^+N$ search

Signal region: $m_N > 270$ MeV/c$^2$

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

$K^+ \rightarrow \mu^+N$ (MC)

Squared missing mass, $(\text{GeV/c}^2)^2$

NA62 (2015): $K^+ \rightarrow \mu^+N$ search

~20M $K_{\mu2}$ decays; <10$^{-5}$ background

$m_N > 200$ MeV/c$^2$

Squared missing mass, $(\text{GeV/c}^2)^2$

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**HNL: possible decay searches**

\[ D^\pm \rightarrow \ell^\pm N \quad O(10^{15}) \text{ decays/year at target} \]

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

Search for decays:

\[ N \rightarrow \pi^\pm \ell^\mp \quad (0.14 \text{ GeV/c}^2 < m_N < 1.9 \text{ GeV/c}^2) \]

\[ N \rightarrow \rho^\pm \ell^\mp \quad (0.8 \text{ GeV/c}^2 < m_N < 1.9 \text{ GeV/c}^2) \]

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).

Proof-of-principle: **2016 data**. Searches for dark photon and axion production at target: prospects are being evaluated.
NA62 run 2015–2018:
- The run is focused on the $K_{\pi\nu\nu}$ measurement ($\text{SES} \sim 10^{-12}$)
- All subdetectors installed and commissioned by 2015
- Detector performances are close to the design ones
- Collecting data at 35% intensity now
- Expect a few SM $K_{\pi\nu\nu}$ events sensitivity with the 2016 data

NA62 run 2021–2024:
- An extensive $K^+/K_L/\pi^0$ rare decay and beam dump programme with existing detector is being developed

Physics outputs:
- First NA62 results with 2015 data relying on hermetic veto rather than high statistics are expected in 2017
- The recent measurement with “old” data (2003–2007) are a training ground and a proof of concept
Backup
TFF measurement with $\pi_0^D$ decay

Differential decay width:

$$\frac{1}{\Gamma(\pi_0^0)} \frac{d^2\Gamma(\pi_0^0)}{dx dy} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} \left(1 + \frac{y^2 + \frac{r^2}{x}}{x}\right) |\mathcal{F}(x)|^2$$

Key issue: radiative corrections (larger effect than TFF)

$$x = \frac{(q_1 + q_2)^2}{m_\pi^2} = \left(\frac{m_{ee}}{m_\pi}\right)^2, \quad y = \frac{2p(q_1 - q_2)}{m_\pi^2 (1-x)}$$

Measurement of the TFF: $F(x) = 1 + ax$

- VMD expectation: TFF slope $a \approx 0.03$
  [Hoferichter et al., EPJC74 (2014) 3180]
- Enters hadronic contribution to $(g-2)_\mu$
  [e.g. Nyffeler, arXiv:1602.03398]
- Influences the $\pi^0 \to e^+e^-$ decay rate
  [Husek et al., EPJC74 (2014) 3010]

Radiative corrections: $\delta(x,y)$

(1) Mikaelian and Smith, PRD5 (1972) 1763

(2) Husek et al., PRD92 (2015) 054027

- Additional diagrams (1$\gamma$ irreducible).
- Radiative photon emission simulated.

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DP production in $\pi^0 \rightarrow \gamma A'$ decay

Batell, Pospelov and Ritz, PRD80 (2009) 095024

\[
\mathcal{B}(\pi^0 \rightarrow \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)
\]

- Probing the Dark Sector.
- Two unknown parameters: mass ($m_{A'}$) and mixing ($\varepsilon^2$).
- Sensitivity to DP for $m_{A'} < m_{\pi^0}$.
- Loss of sensitivity to $\varepsilon^2$ as $m_{A'}$ approaches $m_{\pi^0}$, due to kinematical suppression of the $\pi^0 \rightarrow \gamma A'$ decay.

valid for $\varepsilon^2 \ll 1$

$\text{BR}(\pi^0 \rightarrow \gamma A') / \varepsilon^2$ vs $m_{A'}$
DP decays into SM fermions

Accessible in $\pi^0$ decays: assuming decays only into SM fermions,

$$\Gamma_{A'} \approx \Gamma(A' \rightarrow e^+e^-) = \frac{1}{3} \alpha \varepsilon^2 m_{A'} \sqrt{1 - \frac{4m_e^2}{m_{A'}^2}} \left(1 + \frac{2m_e^2}{m_{A'}^2}\right) \approx \alpha \varepsilon^2 m_{A'}/3$$

For $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10$ MeV/c$^2$, prompt $A'$ decay (z vertex resolution $\sim 1$ m). Therefore $\pi^0_d \rightarrow e^+e^-\gamma$ is an irreducible background.
Prospects for $K^\pm \rightarrow \pi^\pm A'$, $A' \rightarrow l^+l^-$

Comparison of ($K^\pm \rightarrow \pi^\pm A'$, $A' \rightarrow e^+e^-$, $m_{A'} > m_{\pi^0}$) vs ($\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$, $m_{A'} < m_{\pi^0}$):

- Lower irreducible background: $BR(K^\pm \rightarrow \pi^\pm e^+e^-) \sim 10^{-7}$ vs $BR(\pi^0_D) \sim 10^{-2}$.
- Higher acceptance ($\times 4$), favourable $K/\pi^0$ flux ratio ($\times 4$).
- Therefore the expected BR limits: $BR(K^\pm \rightarrow \pi^\pm A') \sim 10^{-9}$ vs $BR(\pi^0 \rightarrow \gamma A') \sim 10^{-6}$.
- However $BR(K^\pm \rightarrow \pi^\pm A')/BR(\pi^0 \rightarrow \gamma A') \sim 10^{-4}$, expected $\varepsilon^2$ limits are $\varepsilon^2 \sim 10^{-5}$.
World data is dominated by the KTeV measurement from $K_L \rightarrow 3\pi^0$: 794 candidates with 7% background.

Measurement:

$BR(\pi^0_{ee}, x>0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$.

Extrapolation:

$BR(\pi^0_{ee}) = (7.48 \pm 0.29 \pm 0.25) \times 10^{-8}$.

[PRD 75 (2007) 012004]

SM prediction: loop-induced and helicity-suppressed decay.

Naïve estimate:

$BR(\pi^0_{ee}) \sim (\alpha m_e/m_{\pi^0})^2 \sim 10^{-9}$.

Detailed calculations:

$BR(\pi^0_{ee}) = (6.23 \pm 0.09) \times 10^{-8}$.

[Dorokhov et al., PRD75 (2007) 114007, Husek et al., EPJ C74 (2014) 3010]

Experiment vs theory: $\sim 3\sigma$ discrepancy.
NA48/2 data: $K^\pm \rightarrow \pi^\pm \pi^0$, $\pi^0 \rightarrow e^+e^-$

$K^\pm \rightarrow \pi^\pm e^+e^-$

NA48/2 data

NA48/2 data: the $m_{\pi ee}$ signal region

$\gamma$ conversions: multiple $e^+e^-$ pairs

Signal region

$K^\pm \rightarrow \pi^\pm \pi^0_D$

$K^\pm \rightarrow \pi^\pm \pi^0_{DD}$

NA48/2: about 300 events collected, but signal/background < 1.

Can be better at NA62.

E. Goudzovski / Birmingham, 2 November 2016
The E949 $K^+ \rightarrow \pi^+ X$, $X$ invisible analysis:

- $K^+ \rightarrow \pi^+ X$ search (where $X$ is invisible)
- $\text{BR}(\pi^0 \rightarrow \text{invisible}) < 2.7 \times 10^{-7}$ at 90% CL

$K^+ \rightarrow \pi^+ X$ excluded at 95% CL

- DP exclusion assuming $\text{BR}(A' \rightarrow \text{invisible}) = 1$
- Non-trivial limits on DP phase space
- Including the $(g-2)_\mu$ favoured band, assuming invisible DP decays.

$\text{BR}(\pi^0 \rightarrow \text{invisible}) < 2.7 \times 10^{-7}$ at 90% CL

$K^+ \rightarrow \pi^+ X$ excluded at 95% CL

Non-trivial limits on DP phase space
Including the $(g-2)_\mu$ favoured band, assuming invisible DP decays.

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Non-trivial limits on DP phase space
Including the $(g-2)_\mu$ favoured band, assuming invisible DP decays.

$\text{BR}(\pi^0 \rightarrow \text{invisible}) < 2.7 \times 10^{-7}$ at 90% CL
Kaons at CERN 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); $<p_{KL}> = 2 \text{ GeV/c}$
- 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: feasibility and sensitivity study
- 400 GeV protons; $<p_{KL}> \sim 100 \text{ GeV/c}$: complementary approach to KOTO.
- 60 SM events in 5 years with $S/B \approx 1$.
- Protons required: $5 \times 10^{19}$ (NA62×10): target area & transfer line upgrade.
- Re-use NA62 infrastructure and parts of detector (LKr calorimeter; muon system).

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