Searching for new physics at Kaon experiments at CERN

Chris Parkinson, on behalf of NA62
CLFV 2016
21st June 2016
Outline

• An introduction to Kaon experiments at CERN

• Recent results (published or underway) from older Kaon experiments at CERN

• An introduction to the NA62 experiment

• Physics prospects of the NA62 experiment
Many Kaon decays can proceed, or are enhanced, by contributions from new physics particles

Kaon experiments at CERN are characterised by huge numbers of Kaon decays with low backgrounds, making Kaon experiments an ideal laboratory in which to search for new physics processes

With a 20% branching fraction to $K^+\rightarrow\pi^+\pi^0$, Kaon experiments are also $\pi^0$ factories

Results from CERNs Kaon physics programme:
- Inflaton or heavy (majorana) neutrino in $K^+\rightarrow\pi^+\mu^+\mu$ decays (analysis completed, paper in preparation)
- Dark photons in Dalitz decays of the $\pi^0$
- Heavy neutrino production in $K^+\rightarrow\mu^+N$ decays (analysis underway)
- Heavy neutrino, or other BSM particles, affecting the ratio of $K^+\rightarrow\mu^+\nu$ and $K^+\rightarrow e^+\nu$ branching fractions
### Recent history of NA experiments

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<tr>
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<th>Notes</th>
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**NA62:** ~200 participants of 29 institutions
Na62: ~200 participants of 27 institutions

Recent history of NA experiments

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Kaon physics at CERN

Results

Prospects

21/06/2016
Chris Parkinson
CLFV2016
Searching for new physics at Kaon experiments at CERN
Kaon decay-in-flight experiments at CERN

- SPS Protons @ 400 GeV steered to Beryllium target (T10)
- Secondary hadron beam – 6% Kaons (70% pions, rest = protons, electrons*)

*electrons removed from beam before reaching NA62
The NA48/2 and NA62_{RK} detector

- Momentum select
- Vacuum Decay Volume 100m long
- Spectrometer immersed in Helium gas with dipole magnet
- EM calorimeter
- Hadron calorimeter
- Muon detector with iron filter
The beam parameters were modified for the NA62_{RK} experiment to give a more favourable environment for measuring $R_K$

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PHYSICS RESULTS FROM NA62_{RK} AND NA48/2
• Results from CERNs Kaon physics programme:
  1. Heavy neutrino and/or other BSM particles affecting the ratio of \( K^+ \rightarrow \mu^+ \nu \) and \( K^+ \rightarrow e^+ \nu \) branching fractions
  2. Inflaton or heavy Majorana neutrino in \( K^+ \rightarrow \pi \mu \mu \) (analysis completed, paper draft in preparation)
  3. Dark photons in Dalitz decays of the \( \pi^0 \)
• **Value of** $R_K$ **can be precisely calculated in the SM**

$$R_K^{SM} = \frac{\Gamma(K \rightarrow e\nu(\bar{\nu}_B))}{\Gamma(K \rightarrow \mu\nu(\bar{\nu}_B))} = \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \left( 1 + \delta R_K^{EM} \right) = 2.477(1) \times 10^{-5}$$

• $R_K$ **is sensitive to:**
  - Ratio of mixing parameters of 4th neutrino $U_{e4}/U_{\mu4}$ [JHEP 1302 (2013) 048]
  - LFV loop diagrams in e.g. SUSY models at $O(10^{-3})$ [EPJ C72 (2012) 2228]
World’s most precise measurement of $R_K$ [PLB 719 (2013) 326]

$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$

$= 2.488(10) \times 10^{-5}$

$\Delta r_K = (4 \pm 4) \times 10^{-3}$

0.4% precision

$\Delta r_K = R_K(NA62)/R_K(SM) - 1$

$M_K$ enhancement

NA62 excluded

[Abada et al. JHEP 1402 (2014) 091]
Search for lepton number violation

- The NA48/2 data contains \( \sim 3.5k \) \( K^+ \to \pi^+\mu^+\mu^- \) candidates [PLB697 (2011) 107]
- The same data can be used to search for the \( K^+ \to \mu^+\mu^+\pi^- \) (LNV) decay

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

- Interpret the results as a search for Majorana neutrinos mediating the $K^+ \rightarrow \mu^+ (\mu^+ \pi^-)$ (LNV) decay
- Search is valid for $N_M$ with $240 \approx m_N \approx 400$ MeV

For $N_M$ with lifetime $\tau = 100\text{ps}$, **production x decay** limits set at $\sim 10^{-10}$ (90% CL)
Search for lepton number conserving N

- Interpret the results as a search for heavy neutrino mediating the $K^+ \rightarrow \mu^+(\pi^+\mu^-)$ (LNC) decay
- Peak search in the $\pi^+\mu^-$ mass distribution

- For $N_M$ with lifetime $\tau=100\,\text{ps}$, **production x decay** limits set at $\sim 10^{-9}$ (90% CL)
Search for inflatons

- Interpret the results as a search for inflatons (X) mediating the $K^+ \rightarrow \pi^+(\mu^+\mu^-)$ (LNC) decay
- Peak search in the $\mu^+\mu^-$ mass distribution

For X with lifetime $\tau=100\text{ps}$, production x decay limits set at $\sim 10^{-9}$ (90% CL)
Search for dark photons

- The $\pi^0 \rightarrow \gamma ee$ decay can be mediated by a dark photon ($A', U$)
- Can be isolated in NA48/2 data via $K^+ \rightarrow \pi^+ \pi^0$ and $K^+ \rightarrow \pi^0 \mu^+ \nu$ decays
- Peak search in the $e^+e^-$ mass distribution

$N(K^+ \rightarrow \pi^+ \pi^0) = 1.38 \times 10^7$

$N(K^+ \rightarrow \pi^0 \mu^+ \nu) = 0.31 \times 10^7$

[PLB 746 (2015) 178-185]
Search for dark photons

- No local significance greater than $3\sigma \rightarrow$ no hint of the dark photon

- NA48/2 constraints exclude dark photon explanation of the $(g-2)_\mu$ discrepancy

[PLB 746 (2015) 178-185]
THE NA62 EXPERIMENT
The NA62 detector is primarily designed to collect 100 $K^+ \rightarrow \pi^+ \nu \nu$ events with only 10 background events. Since the $K^+ \rightarrow \pi^+ \nu \nu$ branching fraction is $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \nu) = (9.11 \pm 0.72) \times 10^{-11}$, this implies a huge number of $K^+$ decays and background reduction at the level of $10^{-12}$.

This requires:
- A more intense secondary beam from the target, which implies a stringent trigger system based on detectors with excellent timing resolution.
- Efficient vetoing of photons (particularly from $\pi^0$ decays), electrons, and muons.
- Accurate momentum and energy measurement of kaon decay products.

These requirements (often inverted!) also make NA62 the perfect laboratory for searches for exotic particles. Development of a trigger strategy for exotic processes is critical.
Kaon decay-in-flight experiments at CERN

- Beam intensities raised by about 4x
- 30x larger acceptance (solid angle) due to improved beamline optics

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The NA62 detector

- **Target**
  - Momentum select

- **NA62 CHOD**
  - New spectrometer, now in vacuum, with stronger $p_T$ kick

- **EM calorimeter**

- **New hadron calorimeter**

- **New muon detector with iron filter**

- **CERN SPS**

- **CEDAR/KTAG:** Measure Kaon time

- **GTK:** Measure Kaon momentum

- **12x photon vetoes**

- **Vacuum Decay Volume:** 65m long

- **RICH**

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**21/06/2016**

Chris Parkinson

CLFV2016

Searching for new physics at Kaon experiments at CERN
$K^+$ tagging – CEDAR/KTAG

- Kaons are tagged with the CEDAR/KTAG system
- CEDAR – collects Cherenkov light with fixed diaphragm
- KTAG – 8-fold PMT array with $\sigma_t \approx 80$ ps
- Nominal Kaon rate $\approx 45$ MHz
STRAW spectrometer

- Position and momentum of $\pi^+$ measured by the STRAW spectrometer
- Straw tubes operated in vacuum – very low material budget

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- $\sigma_p/p \approx 0.32\% \oplus 0.008\%$ [GeV/c]
  - Comparable momentum resolution to muons in LHCb [LHCb muons 2015]
NA62 Charged Hodoscope

- NA62 Charged Hodoscope (NA62CHOD)
- New for 2016
- Designed as a simple charged particle trigger with time resolution of order ~1ns

2016 data
RICH detector

- Ring Imaging Cherenkov detector
- **Offline:** Particle identification for particles with $15 < p < 35$ GeV/c
- **Trigger:** Charged particle trigger with time resolution less than 100ps
RICH detector

- Ring Imaging Cherenkov detector
- Offline: Particle identification for particles with $15 < p < 35$ GeV/c
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Plot from CERN Courier article
Muon veto system (MUV)

- MUV system formed of two calorimeters (MUV1, MUV2) plus a segmented layer of plastic scintillator (MUV3)

- **Offline:** MUV1&MUV2 provide muon rejection
- **Trigger:** MUV3 provides muon rejection with time resolution of \( \approx 450 \text{ ps} \)

MUV1 and MUV2 information combined with LKr

2014 data

Candidate time resolution: 450ps.
Hermetic photon veto

• Hermetic photon veto built from multiple detector systems
• **Small Angles Vetoes** (IRC and SAC) cover from 0 to 1.0 mrad
• The **LKr calorimeter** covers from 1.0 to 8.5 mrad
• **Large Angles Vetoes (LAV)** is formed of 12 stations, which are distributed along the experiment to cover from 8.5 to 50 mrad

• **Trigger:**
  Information from **LAV12** is available
  Information from **IRC and SAC** can be combined with the **LKr**

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NA62 Preliminary 2015 data
Electromagnetic calorimetry

- The **Liquid Krypton Calorimeter**, as used in NA48
- Measures particle energy with energy resolution comparable to e.g. CMS ECAL

\[
\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E(\text{GeV})}} \oplus \frac{9\%}{E(\text{GeV})} \oplus 0.42\%
\]

\[(\sigma_E/E \approx 1\% \text{ at } 10 \text{ GeV})\]

- **Offline**: provides separation of electrons, hadrons, and muons
- **Trigger**: total energy deposition information available
NA62

- Construction complete: Summer 2014
- Pilot physics run: October – December 2014
- Detector commissioning: June – November 2015
NA62

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NA62 data-taking – past, present and future

- 2014 – Pilot Physics run (initial setup of experiment, first look at data)
- 2015 – beam time mostly dedicated to TDAQ and detector commissioning, nevertheless, $10^{10}$ events collected at low intensity with minimum bias triggers
- 2016 to present – commissioning and data-taking with exotics trigger
- 2016-2017-2018 – data-taking for $K^+ \rightarrow \pi^+ \nu \nu$, run exotics trigger in parallel
The NA62 L0 Trigger in 2016

- The lowest-level of the NA62 trigger system (L0) is implemented in hardware, based on FPGA technology.

- A **multiple track** trigger (MT) can be built requiring signals in 10 RICH PMTs and two (NA62)CHOD quadrants.

- **Dielectron trigger**: **multiple track** + more than 10 GeV of energy in the LKr.

- **Dimuon trigger**: **multiple track** + signals in two MUV3 tiles.

- **LFV (muon-electron) trigger**: **multiple track** + more than 10 GeV of energy in the LKr and signal in one MUV3 tile (selects $K^+ \rightarrow \pi \mu e$ decays).

- In simulations the total rate from the above L0 triggers $\sim$ few 100 kHz, which is sufficiently low to run in parallel to the $K^+ \rightarrow \pi^+ \nu \nu$ trigger.

- Validation of the trigger rates with data is **currently underway**.
PHYSICS PROSPECTS OF NA62
Searching for HNL production

- Can also search for production of HNL in $K^+ \rightarrow \mu^+ N$ decays
- $K^+ \rightarrow \mu^+ N$ events appear as peaks in the $K^+ \rightarrow \mu^+ \nu$ squared missing mass spectrum
- Note: Production searches are model-independent

**NA62$_{RK}$ (2007): $K^+ \rightarrow \mu^+ N$ search**

- $\sim 18 \text{M } K^+ \rightarrow \mu^+ \nu$ decays
- Pink histogram is simulated
- $K^+ \rightarrow \mu^+ N$ events with BF = $1 \times 10^{-4}$

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

- $\sim 20 \text{M } K^+ \rightarrow \mu^+ \nu$ decays
- $\sim 10^{-5}$ background

$m_N > 200 \text{ MeV/c}^2$
Searching for HNL production

- Can also search for production of HNL in $K^+\rightarrow\mu^+N$ decays
- Production searches are model-independent
- Most stringent limits are set by Kaon decay measurements

Global limits on $|U_{\mu 4}|^2$ as a function of HNL mass

[Graph showing limits on $|U_{\mu 4}|^2$ as a function of HNL mass]
Lifting of the $R_K$-suppression by the HNL means there could be a similar number of $K^+ \rightarrow e^+ N$ events as $K^+ \rightarrow \mu^+ N$

Limits on $K^+ \rightarrow e^+ N$ are much weaker than those of $K^+ \rightarrow \mu^+ N$

$K^+ \rightarrow e^+ N$ background small enough for stringent limits to be set on this decay
Physics prospects

- $R_K$ measurement expected to improve by a factor of 2-4x at NA62
- Expect background reduction and larger sample of $K^+\rightarrow\pi\mu\mu$ decays, expect improved limits down to $10^{-12}$
Physics prospects

- Searches for $K^+ \rightarrow \pi \mu e$ have potential to probe to $10^{-12}$

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- Sensitivity to dark photons with LFV couplings, masses from 100 to 350 MeV
• Searches for $K^+ \rightarrow \pi \mu e$ have potential to probe to $10^{-12}$

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• Dark photon search in $\pi^0 \rightarrow \gamma ee$ already background dominated, expect 10x improvement in limit

* plot contains published limits up to 2015
Searches for HNL from the target

- HNL can be produced in meson decays at the T10 target
- These HNL can then decay inside the NA62 fiducial volume
- With zero background events, can probe beyond current limits
- Proof-of-principle from 2016 data: searches for dark photon and axion production at the target. Prospects for these searches are being evaluated
Summary

• The long history of Kaon experiments at CERN continues with NA62

• The previous experiments, NA48/2 and NA62RK continue to produce results related to ‘exotic’ processes including: dark photons; inflatons; heavy (majorana) neutrinos in production and decay.
  – New world-best limits on the LNV decay $K^+ \to \mu^+\mu^+\pi^-$

\[
\begin{align*}
N(\mu^\pm\mu^\pm) &= 1 \\
N_{bkg} &= 1.16 \pm 0.87 \\
\therefore \quad BR(K^+ \to \pi^+\mu^\pm\mu^\pm) &< 8.6 \times 10^{-11} \ [90\% \ CL]
\end{align*}
\]

• The NA62 experiment is a substantial upgrade over previous experiments, providing about 70x more kaon decays with much better background rejection

• There are planned and current searches for exotic processes at NA62

• Watch this space for more information!