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
Why search for NP at Kaon experiments

- Many Kaon decays can proceed, or are enhanced, by contributions from new physics particles
- To study these (rare) processes, need precise measurement of many Kaons with low backgrounds
- Kaon experiments at CERN fulfil these characteristics, making Kaon experiments an ideal laboratory in which to search for new physics processes
- Kaon experiments are also $\pi^0$ factories ($K^+\rightarrow\pi^+\pi^0$ branching fraction = 20%)
- 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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**NA62**: ~200 participants of 29 institutions

Kaon physics at CERN
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### Kaon physics at CERN

**Results**
- NA62: ~200 participants of 27 institutions
- 1984 ↓ 1990: NA31 \((K_S/K_L)\)
- 1997 ↓ 2001: NA48 \((K_S/K_L)\)
- 2002: NA48/1 \((K_S/\text{hyperons})\)
- 2003 ↓ 2004: NA48/2 \((K^+/K^-)\)
- 2007 ↓ 2008: NA62 \(R_K\) phase \((K^+/K^-)\)

**Prospects**
- 2003 ↓ 2004: NA48/2 \((K^+/K^-)\)
- 2007 ↓ 2008: NA62 \(R_K\) phase \((K^+/K^-)\)
- 2014 ↓ 2018: NA62 \((K^+)\)
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\textsubscript{RK} detector

CERN

SPS

Target

Momentum select

Vacuum Decay Volume
100m long

Charged hodoscope

EM calorimeter

Muon detector with iron filter

Spectrometer immersed in Helium gas with dipole magnet

Hadron calorimeter

21/06/2016

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Searching for new physics at Kaon experiments at CERN
The NA48/2 and NA62$_{RK}$ experiments

- The beam parameters were modified for the NA62$_{RK}$ experiment to give a more favourable environment for measuring $R_K$

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<td>Data taking</td>
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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

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

$R_K$ 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]
**$R_K$ at NA62**

- **World’s most precise** measurement of $R_K$ [PLB 719 (2013) 326]

$$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$$
$$= 2.488(10) \times 10^{-5} \quad \text{0.4\% precision}$$
$$\Delta r_K = (4 \pm 4) \times 10^{-3}$$

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**Diagram: $\Delta r_K = R_K(\text{NA62})/R_K(\text{SM}) - 1$**

- $M_K$ enhancement
- $m_{\nu}$
- $\text{NA62 excluded}$

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[Abada et al. JHEP 1402 (2014) 091]

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Search for lepton number violation

- The NA48/2 data contains \( \sim 3.5k K^+ \rightarrow \pi^+ \mu^+ \mu^- \) candidates [PLB697 (2011) 107]
- A re-analysis was made to improve the search for the \( K^+ \rightarrow \mu^+ \mu^+ \pi^- \) (LNV) decay

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

- Interpret the results as a search for Majorana neutrino [PLB 620 (2005) 17] 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 [PLB 620 (2005) 17] 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 $\times$ decay limits set at $\sim 10^{-9}$ (90% CL)
Search for inflatons

• Interpret the results as a search for inflatons [PLB 639 (2006) 414] 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 $\pi^0 \rightarrow \gamma e^+ e^-$ 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
NA62 and exotic searches

• 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 $B(K^+ \rightarrow \pi^+ \nu \nu) = (9.11 \pm 0.72) \times 10^{-11}$, 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

New spectrometer, now in vacuum, with stronger $p_T$ kick

NA62 CHOD

New muon detector with iron filter

CEDAR/KTAG: Measure Kaon time

GTK: Measure Kaon momentum

Vacuum Decay Volume 65m long

12x photon vetoes

RICH

EM calorimeter

New hadron calorimeter
$K^+$ 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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- $\sigma_p/p \approx 0.32\% \oplus 0.008\% p [\text{GeV/c}]$
  - 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
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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

*MU*2014 data

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Searching for new physics at Kaon experiments at CERN
**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**
Electromagnetic calorimetry

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

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

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

- **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 (1% of nominal) with minimum bias triggers
- 2016 to present – commissioning and data-taking with exotics trigger, at between 3% and 20% of nominal intensity
- 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 10GeV of energy in the LKr

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

• **LFV (muon-electron) trigger**: multiple track + more than 10GeV 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 ~ 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$18M $K^+\rightarrow\mu^+\nu$ decays
Pink histogram is simulated $K^+\rightarrow\mu^+N$ events with BF = 1x10^{-4}

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

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

m_N > 200 MeV/c^2

Squared missing mass, (GeV/c^2)^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 $|U_{\mu4}|^2$ as a function of HNL mass

PHYSICAL REVIEW D 93, 033005 (2016)

[Graphical representation of global limits on $|U_{\mu4}|^2$ as a function of HNL mass, showing data from various experiments such as KEK (1982), NA62-R$_K$, NA62-R$_K$, SES, NA62 minimum bias data 2015, and E949 (2015).]
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 (see link) production at the target. Prospects for these searches are currently 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 $K^+\rightarrow\mu^+\mu^+\pi^-$

  \[ N(\mu^\pm\mu^\pm) = 1 \]
  \[ N_{\text{bkg}} = 1.16\pm0.87 \]

  \[ \text{BR}(K^\pm\rightarrow\pi^\mp\mu^\pm\mu^\pm) < 8.6\times10^{-11} \text{ [90\% CL]} \]

• 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!