Search for exotic decays with NA62

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Outline

Motivation for exotic decay searches
Introduction to the NA62 experiment
Recent results from NA62
Prospects of the NA62++ experiment

The NA62 detector
Motivation

No convincing signature of new physics discovered at the energy frontier (LHC)

Shift in interest towards the intensity frontier

Searches for light particles with feeble coupling to the SM (dark sector portals)
Motivation

No convincing signature of new physics discovered at the energy frontier (LHC)

Shift in interest towards the intensity frontier

Searches for light particles with feeble coupling to the SM (dark sector portals)

Including: dark photon ($A'$), dark scalars ($S$), axion-like particles ($ALP$), heavy neutrino ($N$)

All of these could be discovered in the NA62 experiment at CERN
The NA62 experiment at CERN

The NA62 collaboration has about 200 members from 28 institutes around the world.


Broad physics programme:
- Main physics goal: $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- Rare/forbidden kaon decays
- Exotic processes

New results
Talk by J. Pinzino
Wed 15:40
The NA62 experiment

The CERN North Area is host to several experiments
- NA61, **NA62**, NA64, ProtoDUNE, ...

For **NA62**:

- 400 GeV/c protons impinge on the T10 target
  - $10^{12}$ protons on target per spill
  - Typically two 5 second spills every 32 seconds

Produces a beam of positive secondary hadrons
- Momentum selected at $p = 75$ GeV ± 1%
- 750 MHz of particles in the beam (6% $K^+$ fraction)
The NA62 experiment

Beam measurement
- **KTAG**: $K^+$ tagging, $\sigma_t = 70$ ps
- **GTK**: beam spectrometer, $\sigma_t = 200$ ps
- **CHANTI**: veto for scattered particles
- **Vacuum**: fiducial decay volume

Daughter particle measurements:
- **STRAW**: spectrometer, $\sigma_p = (0.3 \pm 0.005\cdot p)\%$ [GeV]
- **CHOD**: hodoscope, $\sigma_t = 200$ ps
- **RICH, LKr**: particle identification ($\pi / \mu / e$)
- **LAV/LKr/IRC/SAC**: fully hermetic photon vetoes
- **MUV1,2,3**: muon vetoes
The NA62 experiment

About 20% of $K^+$ decay inside the fiducial volume (5 MHz of $K^+$ decays)

From 2 years running at nominal intensity:
- Observe $O(10^{13})$ $K^+$ decays in fiducial volume
- Observe $O(10^{12})$ $\pi^0$ decays, since $B(K^+ \rightarrow \pi^+\pi^0) \approx 20$

Huge data samples and powerful detector make NA62 a perfect laboratory for exotic searches
Search for heavy neutrino production


**Analysis principle:**
- Heavy neutrinos produced in $K^+ \rightarrow \ell^+ N$, ($\ell = e, \mu$) due to mixing with SM neutrinos
- $N$ long lived and escapes the detector
- $B(K^+ \rightarrow \ell^+ N) = B(K^+ \rightarrow \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_\ell|^2$
  - $\rho_\ell(m_N)$ is a phase-space factor
  - $U_\ell$ is the mixing strength

**Search strategy:**
1. Search for excess in missing mass spectrum:
   $$m_{\text{miss}}^2 = (P_K - P_\ell)^2 = m_N^2$$
2. Count $n_{\text{sig}}$ in sliding mass window across $m_{\text{miss}}^2$
3. Convert $n_{\text{sig}}$ to limit on $|U_\ell|$
Search for heavy neutrino production

**Data used:**
- Number of $K^+$ are $n_K^e = 3 \times 10^8$ and $n_K^\mu = 1 \times 10^8$
- Collected over five days in 2015 with a minimum-bias trigger running at ~1\% nominal intensity

**Results:**
- Limits on $n_{\text{sig}}$ set using Rolke-Lopez method
- Limits on $|U_\ell|$ at $O(10^{-7})$ for both electron and muon modes
- Improved limits on $|U_\ell|$ from $170 - 448$ MeV/$c^2$
- Improved limits on $|U_\mu|$ above $300$ MeV/$c^2$

Future prospects very promising: $|U_\ell| < 10^{-8}$
Search for $A'$ in $\pi^0$ decays


Analysis principle:
- Dark photon produced in $\pi^0$ decay: $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$ through kinematic mixing with the SM photon
- Rate driven by mixing strength $\epsilon$:

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{\mu\nu}^{\text{dark}}$$

Search strategy:
1. Search for excess of events in missing mass spectrum:
   $$m^2_{\text{miss}} = (P_K - P_\pi - P_\gamma)^2 = m^2_{A'}$$
2. Count $n_{sig}$ in sliding mass window across $m^2_{\text{miss}}$
3. Convert $n_{sig}$ to limit on $\epsilon$
Search for $A'$ in $\pi^0$ decays


Data used:
- A subsample of the 2016 data
- About 1% of data collected from 2016 – 2018

Limit setting:
- CLs method used to set limits on $\epsilon^2$ at 90% CL
- No statistically significant excess was observed
Search for $A'$ in $\pi^0$ decays


Data used:
- A subsample of the 2016 data
- About 1% of data collected from 2016 – 2018

Limit setting:
- CLs method used to set limits on $\epsilon^2$ at 90% CL
- No statistically significant excess was observed
- Improved limits from 60 – 110 MeV/c$^2$

Also sets world’s best upper limit on $B(\pi^0 \rightarrow \gamma \nu \bar{\nu}) < 1.9 \times 10^{-7}$ (more than 3 orders of magnitude improvement)
The NA62++ experiment uses the same NA62 apparatus in a “beam dump” mode:

- T10 target is removed, the beam is dumped onto copper ‘TAX’ collimators (takes ~10 minutes to set up)
- All hadrons are absorbed in the TAX material, but dark sector particles can pass into the fiducial volume

NA62++ can collect $O(10^{18})$ protons on target (POT) in $O(3)$ months (protons at $p = 400$ GeV/c) Possibility to run in this mode in 2023
The NA62++ experiment

PBC BSM working group report. arxiv:1901.09966

The physics prospects of NA62++ have been studied as part of the ‘Physics Beyond Colliders – Beyond the Standard Model’ working group

The following slides show NA62++ prospects assuming $O(10^{18})$ POT

The limits are set at 90% CL, and are compared to other results expected on a 5-year timescale

The results of background studies based on $O(10^{16})$ POT are included in the limits

Improvements to the NA62++ setup (upstream veto, beamline modifications, higher intensity) are not included here, but initial studies are promising
Dark photon $A'$ decaying visibly

NA62++ can improve limits on the $A'$ parameter space

$A' \rightarrow \mu^+\mu^-$ and $A' \rightarrow e^+e^-$ included here

NA62 limits comparable with those possible at SeaQuest (not shown here)

Strength of mixing with SM photon

mass of the dark photon
Dark scalar $S$

NA62++ can improve limits on the $S$ parameter space

$S \rightarrow \mu^+ \mu^-$ important here

NA62 limit comparable with those possible at SeaQuest

Also $K^+ \rightarrow \pi^+ inv$ and $K^+ \rightarrow \pi^+ S, S \rightarrow \mu^+ \mu^-$ accessible to NA62 in $K^+$ mode
Heavy neutrino $N$

NA62++ can improve limits on the $N$ parameter space

All $N$ decays with at least two charged tracks are considered, assuming zero background

Electron coupling dominance: $U_{e}^{2} : U_{\mu}^{2} : U_{\tau}^{2} = 1 : 0 : 0$
Heavy neutrino $N$

NA62++ can improve limits on the $N$ parameter space.

All $N$ decays with at least two charged tracks are considered, assuming zero background.

Muon coupling dominance: $U^2_e : U^2_\mu : U^2_\tau = 0 : 1 : 0$
Heavy neutrino $N$

NA62++ can improve limits on the $N$ parameter space

All $N$ decays with at least two charged tracks are considered, assuming zero background
**ALP** with photon couplings

NA62++ can **improve limits** on the *ALP* parameter space.

Limits for *ALPs* with gluon and fermion couplings currently being computed.
Summary

The NA62 experiment is a powerful laboratory to make searches for exotic decays

Results of recent searches for the exotic decays $K^+ \rightarrow \ell^+ N$ and $\pi^0 \rightarrow \gamma A'$ were presented

Worlds-best limits have been set on both the $N$ and $A'$ parameter spaces respectively

The prospects for the NA62++ “dump mode” experiment were presented

Searches for exotic decays at NA62++ can improve limits in a variety of models, including dark photons ($A'$), dark scalars ($S$), axion-like particles ($ALP$), heavy neutrinos ($N$)
Dark photon decaying visibly

15-year timescale

SeaQuest limit $\approx$ FASER2
Dark photon $A'$ decaying visibly

Non-PBC limits (15 years)

Strength of mixing with SM photon

mass of the dark photon
Dark scalar $S$

15 year timescale

Strength of mixing with SM Higgs
Heavy neutral leptons

Electron coupling dominance: $U_{e}^{2} : U_{\mu}^{2} : U_{\tau}^{2} = 1 : 0 : 0$

15 year timescale
Heavy neutral leptons

Muon coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$

15 year timescale
Heavy neutral leptons

Tau coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 0 : 1$

15 year timescale
ALP with photon couplings

15 year timescale