Hidden sector searches at NA62

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on behalf of NA62 collaboration

Light dark matter @ accelerators 2017

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Outline

- NA62 experiment
- Hidden sector searches in NA62
- Expected sensitivities for the hidden sector
- Preliminary studies on 2016 data in beam mode
- Conclusions
NA62 experiment

Kaon physics at CERN:
- Fixed target experiments at CERN SPS
- Kaon decay-in-flight

Currently in NA62:
- ~200 participants
- 29 institutions from 13 countries

Main goal:

BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) measurement with $\mathcal{O}(10\%)$ precision

SM prediction:

$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$


Experimental status (E787, E949):

$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3_{-10.5}^{+11.5}) \times 10^{-11}$


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Hidden sector searches at NA62
Background Process | Branching ratio
---|---
$K^+ \rightarrow \pi^+\pi^0$ | 0.2066
$K^+ \rightarrow \mu^+\nu_\mu$ | 0.6356
$K^+ \rightarrow \pi^+\pi^+\pi^-$ | 0.0558
SPS protons:
400 GeV/c
$10^{12}$ Proton on target (PoT)/sec on spill
3.5 sec spill
NA62 layout


SPS protons:
- 400 GeV/c
- 10^{12} PoT/sec on spill
- 3.5 sec spill

Secondary beam:
- 75 GeV/c, 1% bite
- 100 μrad
- 60 × 30 mm²
- $K^+(6\%)/\pi^+(70\%)/p(24\%)
- 750 MHz at GTK3

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Kaon decay region:
60 m
~5 MHz
O(10^{-6}) mbar
Performances
✓ Excellent time resolution $\mathcal{O}(100 \text{ ps})$ to match beam and daughter particle information
✓ Kinematics: rejection of main $K$ modes $10^4$ via kinematics reconstruction
✓ PID capability: $\mu$ vs $\pi$ rejection of $O(10^7)$ for $15 < p(\pi^+) < 35 \text{ GeV}$
✓ High-efficiency veto: $10^8$ rejection of $\pi^0$ for $E(\pi^0) > 40 \text{ GeV}$
NA62 timescale for $K^+ \to \pi^+\nu\bar{\nu}$ (2016-2018)

Run in 2014: pilot run
Run in 2015: commissioning run
  • commissioning of L0 trigger
  • run up to nominal intensity,
  • $33 \times 10^{11}$ PoT/spill, 3.5 s effective-length spill
Run in 2016: detector commissioning + physics run
  • L1 trigger/detector final commissioning
  • stable run at 40% of the nominal beam intensity
  • the goal is to reach SM-expectation sensitivity $\mathcal{O}(10^{-10})$
Run in 2017: physics run
  • improve on present state of the art (BNL measurement) collecting 14-15 $K^+ \to \pi^+\nu\bar{\nu}$ events
Run in 2018: physics run
  • measurement of $\text{BR}(K^+ \to \pi^+\nu\bar{\nu})$ at 10%

Current run

$K^+ \to \pi^+\nu\bar{\nu}$ physics program
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Hidden sector motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics: \textbf{search for non-gravitational interactions DM-SM}

\textbf{A mediator of a hidden sector might exist}, inducing DM-SM field (\textit{feeble}) interactions; many possible dynamics: vector ($A'$ dark photon), neutrino (HNL), axial (ALP $a$), scalar..

\textbf{Various experimental hints} for hidden sector at MeV-GeV, e.g., $a_\mu$ 3.5-$\sigma$ discrepancy:

![Diagram: Dark Photon ($A'$) Mediation](image1)

![Diagram: ALP ($a$) Enhancement](image2)

\textbf{Feeble interaction:} ultra-suppressed production rate, \textit{very long-lived states}.

E.g.: 1-GeV mass HNL, $\tau \sim 10^{-5}$-$10^{-2}$ s, decay length $\sim 10$-10000 Km at SPS energies, suppression at production $10^{-7}$-$10^{-10}$
Hidden sector searches at NA62 from kaons

Such high-intensity, high-performance setup as NA62 might be suited for these NP searches:

- **Trigger bandwidth for final states other than \( \pi^+ + E_{\text{miss}} \) (used for the \( K^+ \to \pi^+ \nu \bar{\nu} \)) limited.** Some LFV/LNV studies can be performed because involve low-bandwidth trigger:
  - 3 daughter tracks at SES ~ 10^{-11}: \( K^+ \to \pi^+ \mu^\pm e^\mp, K^+ \to \pi^- \mu^- e^+, K^+ \to \pi^- e^+ e^+ \)
  - others because can be made in parasitic mode with the main trigger:
    - search for heavy neutral leptons in \( K^+ \to \mu^+ \nu_h, K^+ \to e^+ \nu_h \)
    - search for \( \pi^0 \to \text{invisible} \), NA62 sensitive at 10^{-8} or better
The NA62 Be-target is followed 20-m downstream by two 1.6-m long, water-cooled, copper collimators, `Target Attenuator eXperimental areas' (TAXes) offering a choice of bores of different apertures for momentum selection.
In dump mode the target can be moved away from the beam and the beam let impinging on the copper. **The TAXes can act as a dump.**

**Heavy Neutral Leptons, Dark Photons, Dark scalars, and ALPS** can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

PS: already in beam mode ~40% of protons do not interact with the target and are dumped onto the TAXes.

- $K^+ \rightarrow \pi^+ \mu^+ e^+$, $K^+ \rightarrow \pi^- \mu^- e^+$, $K^+ \rightarrow \pi^- e^+ e^+$, $K^+ \rightarrow \pi^- \mu^+ \mu^+$ (+ radiative modes)
- $\pi^0 \rightarrow \mu e, 3\gamma, 4\gamma, ee, eeee, invisible$

**NA62 timescale for exotic searches**

NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, LNV/LFV decays, hidden sector searches in K decays
NA62 timescale for exotic searches

- $K^+ \rightarrow \pi^+ \mu^+ e^\mp, K^+ \rightarrow \pi^- \mu^- e^+, K^+ \rightarrow \pi^- e^+ e^+, K^+ \rightarrow \pi^- \mu^+ \mu^+$ (+ radiative modes)
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Run 3 (2021-2023): new program of NP searches for MeV-GeV mass hidden-sector candidates: dark photons, heavy neutral leptons, Axions/ALP’s, etc.
Goal: integrate (1-2) x10^{18} pot in dump mode in Run 3: this corresponds overall to 100-200 integrated days of data taking at 100% proton intensity.
The beam time dedicated to the dump mode will be spread along the years to not disrupt the kaon programme

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Hidden sector searches at NA62
Hidden sector particle at NA62: dump mode

K, B, Bs, D, Ds → lepton HNL
K, B, Bs, D, Ds → semi-leptonic modes

At SPS energies:
\[ \sigma (pp \rightarrow s \overline{s} \ X) \sim 0.15 \]
\[ \sigma (pp \rightarrow c \overline{c} \ X) \sim 2 \times 10^{-3} \]
\[ \sigma (pp \rightarrow b \overline{b} \ X) \sim 1.6 \times 10^{-7} \]

Heavy neutrino couplings enter both in production and in decay (\(\sim U^2\) process).

SPS proton
400 GeV/c

Dump

K, D, B
photons, neutrons, protons, \(\pi\)
muons from K/\(\pi\) decays
and light resonances, neutrinos, etc..

K, D, B
Lepton

HNL

Lepton

\(\pi\)
Hidden sector particle at NA62: dump mode

**Dark photons**

At SPS energies:
\[ \sigma (pp \to s \overline{s} X) \sim 0.15 \]
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Photon produced in light meson resonances, bremsstrahlung, and QCD processes.
Search for massive particle mixing with the photon and decaying to visible final states (e^+ e^-, \mu^+\mu^-, etc.)
Hidden sector particle at NA62: dump mode

Dump mode

A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:

SPS proton 400 GeV/c

Dump

Muons

HNL

A’

Dark scalars

Neutrinos

Any kind of feebly-interacting long-lived particle (put here your favored model)

An experiment with a long decay volume will allow you to probe low values of couplings (as the lifetime of dark objects ~ 1/coupling^2)
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Search for visible decays of long-lived $A'$

Assume $2 \times 10^{18}$ 400-GeV PoT:

- search for displaced, dilepton decays of dark photons, $A' \rightarrow \mu\mu, ee$
- include trigger/acceptance/selection efficiency
- assume zero-background, evaluate expected 90%-CL exclusion plot

Sensitivity expected to be even higher including:
- direct QCD production of $A'$
- $A'$ production in the TAX (only target considered here)
Search for visible decays of HNL

Assume $2 \times 10^{18}$ 400-GeV PoT:
- search for displaced, leptonic decays $\text{HNL} \rightarrow \pi e, \pi \mu$
- include trigger/acceptance/selection efficiency
- assume zero-background, evaluate expected 90%-CL exclusion plot
Search for visible decays of ALP

Assume $1.3 \times 10^{16}$ ($3.9 \times 10^{17}$) PoT corresponding to 1 day (1 month) runs:

- study ALP Primakoff production [JHEP 1602 (2016) 018] at target
- search for ALP-decay to $\gamma\gamma$ in NA62 fiducial volume, account for geometrical acceptance
- assume zero-background, evaluate expected 90%-CL exclusion plot
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Search for $A' \rightarrow \mu\mu$: test on 2016 data

Statistics corresponds to $\sim 10^{15}$ PoT

**Track quality + acceptance cuts:** forward detectors, CHOD, LKr, MUV3 associated to CHOD, LKr hits in time

**Vertex quality:** two-track distance $< 1$ cm

**Vertex position:** $105 < Z < 165$ m

Test if total momentum $P_{tot} = P_\mu + P_\mu$ stems from target

Background from $K, \pi$ decays concentrated around beam after final collimator

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**Impact parameter of $P_{tot}$ to beam line [cm]**

**Z of closest approach of $P_{tot}$ to beam line [m]**

**Signal region**

**All two tracks vertices**

**PCA vs Z Total M1**

- Entries: 21571
- Mean $x$: 1.265e+04
- Mean $y$: 0.8306
- Std Dev $x$: 1988
- Std Dev $y$: 0.8692

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Search for $A' \rightarrow \mu\mu$: test on 2016 data

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Vertex quality: two-track distance $< 1$ cm

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Test if total momentum stems from target

Further event-level veto conditions:
Additional energy in the LKr $< 2$ GeV
Veto on forward / large angle calorimeters
Veto on charged anti counter

No events selected in the signal region (even with standard $K^+$ beam)
NA62 2016 data: dark photon from $\pi^0$ decay

Decay chain: $K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow A' \gamma, A' \rightarrow invisible$

- **Signature:**
  - 1 photon + missing energy

- **Selection:**
  - $\pi^+$ as in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - $15 < p_{\pi^+} < 35$ GeV/c
  - 1 $\gamma$ in LKr
  - Missing momentum in LKr
  - Extra $\gamma$ veto

- **Background:**
  - Negative tail of $M^2_{miss}$

- **Normalization:**
  - $K^+ \rightarrow \pi^+ \pi^0$ from minimum bias

- $M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$

Minimum bias data: 2 $\gamma$ on LKr, simulate 1$\gamma$ loss

MC:
- $m_{A'} = 30$ MeV
- $m_{A'} = 60$ MeV
- $m_{A'} = 90$ MeV

$M^2_{miss}$ (GeV$^2$)
NA62 2016 data: dark photon from $\pi^0$ decay

NA62 limits in an interesting region; $#K$ decays $\sim 1.5 \times 10^{10}$ (4% 2016 statistics) used
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Conclusions

- NA62 is officially approved to run until LS2 with the main goal of measuring the BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) with 10% accuracy;
- Before LS2 (2018) many searches in the hidden sector will be performed using the kaon beam (new limits on dark photon already investigated).
- After LS2 (2020++) there is a window of opportunity to run NA62 in beam-dump mode to search for hidden particles from charm and beauty decays and pave the way for the next generation experiments (SHiP).
- Preliminary studies with data taken in beam and beam-dump modes show that the background can be kept under control, further improvements in the setup are currently under study.