Search for dark photons at NA62

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on behalf of NA62 collaboration

Rencontres de Moriond QCD and High Energy Interactions

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Hidden sector motivations

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

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

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

![Diagram of a dark photon A'](#)

...or to an ALP a enhancing light-by-light?

![Diagram of an ALP a](#)

**Feeble interaction:** ultra-suppressed production rate, 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 $10^{-7}$-$10^{-10}$
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:
$BR(K^+ \to \pi^+ \nu \bar{\nu})$ measurement with $\mathcal{O}(10\%)$ precision

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


Experimental status (E787, E949):
$BR(K^+ \to \pi^+ \nu \bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$

SPS protons:
400 GeV/c
$10^{12}$ Proton on target (PoT)/sec on spill
3.5 sec spill
SPS protons:  
400 GeV/c  
$10^{12}$ PoT/sec on spill  
3.5 sec spill  

Secondary beam:  
75 GeV/c, 1% bite  
100 μrad  
$60 \times 30$ mm$^2$  
$K^+(6\%)/\pi^+(70\%)/p(24\%)$  
750 MHz at GTK3
**NA62 layout**

[NA62 Detector Paper, JINST 12 (2017), P05025]

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

**Secondary beam:**
- 75 GeV/c, 1% bite
- 100 µrad
- $60 \times 30$ mm$^2$
- $K^+ (6\%) / \pi^+ (70\%) / p(24\%)$
- 750 MHz at GTK3

**Kaon decay region:**
- 60 m
- $\sim 5$ MHz
- $\mathcal{O}(10^{-6})$ 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 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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
Run in 2017-2018: physics run
  • improve on present state of the art (BNL measurement) collecting $\sim 20$ SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events before LS2

Current run

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ physics program
NA62 physics besides $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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

- Lepton flavour violation (LFV) and lepton number violation (LNV) studies
- ultra-rare/forbidden $\pi^0$ decays
- chiral perturbation theory studies from kaon decays
- search for exotic states

Trigger bandwidth for final states other than “$\pi^+ + E_{\text{miss}}$” (used for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$) limited. Some LFV/LNV studies can be performed because involve low-bandwidth trigger

- 3 daughter tracks at SES $\sim 10^{-11}$: $K^+ \rightarrow \pi^+ \mu^\pm e^\mp, \ K^+ \rightarrow \pi^- \mu^+ e^+, \ K^+ \rightarrow \pi^- e^+ e^+, \ K^+ \rightarrow \pi^\pm \mu^\mp \mu^+$

others because can be made in parasitic mode with the main trigger:

- search for heavy neutral leptons in $K^+ \rightarrow \mu^+ \nu_h, \ K^+ \rightarrow e^+ \nu_h$
- search for $\pi^0 \rightarrow \text{invisible}$, NA62 sensitive at $10^{-8}$, search for $\pi^0 \rightarrow A' \gamma$
Several production modes / signals of $A'$ can be studied at NA62

- Search for invisible decays (production in fiducial volume, missing mass signals):
  - From $K^+$ beam: for $K^+ \rightarrow \pi^+ A'$, by product of $K^+ \rightarrow \pi^+ \nu \nu$ [Marciano et al. PRD 892014]
  - From $K^+$ decay daughters: $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow A' \gamma$

Rate scales with square of coupling

Up with intensity, if no background limited, improve from above
Several production modes / signals of $A'$ can be studied at NA62

- Search for visible decays to SM particles (production at target/dump)
  Production from primary beam secondaries: $pN \rightarrow X\pi^0, \pi^0 \rightarrow A'\gamma, A' \rightarrow l^+l^-$
  Production from primary beam: $pN \rightarrow XA', A' \rightarrow l^+l^-$

Rate scales with 4$^{th}$ power of coupling

Sensitivity region shape depends on:
- minimum distance from production point to decay volume (upper curve)
- decay volume acceptance (lower curve)

Up with intensity, if no background limited, improve from below
NA62 in dump mode

A rich field to be explored with minimal upgrades to the present setup: run in “beam-dump” mode with NP searches for MeV-GeV mass hidden-sector candidates like Dark photons, Heavy neutral leptons (HNL), Axions/ALP, etc.

Compact beam dump: ~ 11 λ₁ Cu-based beam-defining collimator (TAX)

High-intensity 400-GeV proton beam: boost charm/beauty, other meson production

$10^{18}$ PoT / nominal year: $10^{12}$ PoT/sec on spill, 100 days/year, 60% run efficiency

$10^{15}$ D$_{(S)}$, $10^{14}$ K, $10^{18}$ $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95
NA62 Run3 plan under discussion

- If needed, run for refining $K^+ \to \pi^+ \nu \nu$

- Present setup for $K^+$ beam + dedicated triggers: LFV/LNV sensitivity studies based:
  $K^+ \to \pi^+ \mu^\pm e^\mp$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$ (+ rad. modes)
  $\pi^0 \to \mu e, 3\gamma, 4\gamma, ee, eee$

- $10^{18}$ POT in run in “beam-dump” mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP’s, etc.

Current run

LS2

Run 3

LS2

**NA62: $K^+ \to \pi^+ \nu \nu$, LNV/LFV decays, hidden sector searches in K decays**

**LFV/LNV @ ultimate sensitivity, hidden sector searches (beam dump)**
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 $M_{miss}^2$

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

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

Data control trigger: 2 $\gamma$ on LKr, simulate 1 $\gamma$ loss

MC:
- $m_{A'} = 60$ MeV
- $m_{A'} = 90$ MeV
- $m_{A'} = 120$ MeV

$M_{miss}^2$ (GeV$^2$)

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Search for dark photons at NA62
NA62 2016 data: dark photon from $\pi^0$ decay

- Limits observed are statistically compatible with fluctuations from the background-only hypothesis.
- NA62 limits in an interesting region; $#K$ decays $\sim 1.5 \times 10^{10}$ (4% 2016 statistics) used.

Limit if $N_{\text{obs}} = N_{\text{bkg}}$

Limit found
- 1-s limit band
- 2-s limit band

$M_{A'}$ (MeV)

$M_{A'}$ (GeV)

Search for dark photons at NA62
Search for visible decays of long-lived $A'$

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

- $A'$ produced (meson decays, bremsstrahlung) from interaction into target
- 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 $A'$ and production in the dump (only target considered here)

$3 \times 10^{17}$ PoT acquired in 2016/17 with di-muon parasitic trigger, $5 \times 10^{16}$ PoT with ee trigger
Zero background assumption: 2016 data

Statistics corresponds to $\sim 10^{15}$ PoT, search for $A' \to \mu\mu$

**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**

NA62
Preliminary

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Search for dark photons at NA62
Zero background assumption: 2016 data

Statistics corresponds to \( \sim 10^{15} \) PoT, search for \( A' \rightarrow \mu\mu \)

**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 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)
Heavy neutrino invisible decay: 2015 data

New result released in 2018 from minimum bias data equivalent to $3 \times 10^8 K^+$ decays analyzed in $K^+ \rightarrow e^+ \nu$ search and to $1 \times 10^8 K^+$ decays analyzed in the $K^+ \rightarrow \mu^+ \nu$ search [NA62 coll. PL B778 137 (2018)]

Squared missing mass: $(P_K - P_e)^2$ [GeV$^2$]

No heavy neutrino signal observed; improvement on $|U_{e4}|^2$ and $|U_{\mu4}|^2$

Major improvements with NA62 2016-2018 higher intensity data sets and fully operational beam tracker

Squared missing mass: $(P_K - P_\mu)^2$ [GeV$^2$]

UL on $|U_{44}|^2$ at 90% CL

HNL mass [MeV]

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Search for dark photons at NA62
Conclusions

- NA62 is officially approved to run until LS2 with the main goal of collecting ~ 20 SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events before LS2.
- 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.
- The current NA62 run can be exploited to evaluate background rejection capability up to $\sim 10^{17}-10^{18}$ POT. 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.
Search for visible decays of HNL

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

- search for displaced, leptonic decays $HNL \rightarrow \pi e, \pi \mu$, HNL production at the TAX
- include trigger/acceptance/selection efficiency
- separately address 3 extreme coupling scenarios [Shaposhnikov, Gorbunov arXiv:0705.1729v2]
- assume zero-background, evaluate expected 90%-CL exclusion plot

$U^2_e : U^2_\mu : U^2_\tau = 52:1:1$

Normal hierarchy of active $\nu$ masses

$U^2_e : U^2_\mu : U^2_\tau = 1:16:3.8$

Normal hierarchy of active $\nu$ masses

$U^2_e : U^2_\mu : U^2_\tau = 0.061:1:4.3$

Normal hierarchy of active $\nu$ masses

$10^{18}$ PoT acquired in 2016/17 with $\mu \pi$ parasitic trigger, few $10^{16}$ PoT with $e \pi$ trigger
Search for visible decays of ALP

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

- 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

Improvements expected already with 1 day of run ($1.3 \times 10^{16}$ POT)
Analysis of 2017 data for $\sim 5 \times 10^{15}$ PoT taken in dump mode in progress