Accelerator-based light particles searches with NA62

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Why light particle searches?

- No evidence so far of NP at $\gtrsim$TeV scale, nor compelling theoretical need for (vacuum «metastable» up to Planck scale...)

- **But** SM uncomplete (neutrino masses & mixing, dark matter, matter-antimatter asymmetry, $\theta_{CP}$ ...)

- NP could be **light** & **feebly coupled to SM**

- Need both high statistics *and* good mass resolution→ **NA62** well suited for searches in the MeV-GeV range

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NA62 @ CERN SPS

Primary beam:
- $p = 400$ GeV SPS protons
- $10^{12}$ protons/effective second

Secondary beam:
- $p = 75$ GeV positive, unseparated
- Total rate: 750 MHz
- $K^+$ rate: 45 MHz

- KTAG: Differential Cerenkov for $K^+$ ID in beam
- CHANTI: Charged veto
- LAV: Large angle photon vetoes
- OPAL lead glass
- RICH: RICH $\mu/\pi$ ID
- 1 atm Ne
- MUV: $\mu$ veto
- Fe/scint

- Beam tracking
- Si pixels, 3 stations
- GIGATRACKER

- Fiducial volume ~60m
- $10^{-6}$ mbar
- 5 MHz $K^+$ decays

- Dipole spectrometer
- 4 straw-tracker stations
- STRAW

- Forward $\gamma$ veto
- NA48 LKr

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Beam and decay tracking with missing mass resolution $10^{-3} \text{ GeV}^2/c^4$
Particle id: $O(10^7) \mu \text{ vs } \pi$ rejection for $15 \text{ GeV} < p < 35 \text{ GeV}$
Photon detection: $O(10^8) \pi^0$ rejection for $E(\pi^0) > 40 \text{ GeV}$
Primary goal: precision measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ (SM $\approx 8 \cdot 10^{-11}$)

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Light particles production at NA62

- **Kaon decays:**
  - $K^+$ decays in the 60 m decay volume with X in final state
  - Signature: missing mass peaks («invisible» modes)
  - Standard data taking $\rightarrow O(10^{13})$ kaon decays sample (by 2018)
  - Limited mass range: $m_X < m($decaying hadron$)$

- **400 GeV protons on target:**
  - X produced at beam target (1 $\lambda_{\text{int}}$ Be) or beam dump (22 $\lambda_{\text{int}}$ Cu)
    Can probe higher $m_X$ range.
  - Signature: visible X decay modes (e.g. $ee,\mu\mu,\mu e,\pi e,\pi\mu,\gamma\gamma$).
  - Standard beam: $N($pot$)$ depending on final state (trigger). **Up to $10^{17}$ pot collected** for specific triggers
  - **Dedicated beam dump runs** (closed TAXES). $10^{18}$ pot in Run3 under consideration.
Standard run vs beam dump

1 $\lambda_{\text{int}}$ Be target for standard data taking

22 $\lambda_{\text{int}}$ Cu collimator (TAX) closed for dump-mode data taking
### Dark sector searches at NA62

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
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<tbody>
<tr>
<td>Dark photon</td>
<td>$-\frac{\varepsilon}{2 \cos \theta_W} F'_\mu \nu B^{\mu \nu}$</td>
</tr>
<tr>
<td>Scalar</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
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<tr>
<td>Axion</td>
<td>$\frac{a}{f_a} F_{\mu \nu} \tilde{F}^{\mu \nu}, \frac{a}{f_a} G_{i, \mu \nu} \tilde{G}<em>{i}^{\mu \nu}, \frac{\partial</em>{\mu} a}{f_a} \bar{\psi} \gamma^{\mu} \gamma^5 \psi$</td>
</tr>
<tr>
<td>Neutrino/HNL</td>
<td>$\gamma_{N} LHN$</td>
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</table>
Dark photon @ NA62

- Extra U(1) massive gauge singlet
- Mixing with SM hypercharge
- \( \varepsilon \) and \( m_{A'} \) are free parameters

Searches at NA62:
- Invisible modes (\( K^+ \rightarrow \pi^+ A' \) or \( K^+ \rightarrow \pi^+ \pi^0 \) and \( \pi^0 \rightarrow \gamma A' \))
- Production at target/dump and decays like \( A' \rightarrow ee \) or \( A' \rightarrow \mu\mu \)
- One $\pi^+$ and one $\gamma$ final state topology
- No need for dedicated trigger
- Data driven background estimation

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

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

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

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Dark photon in $\pi^0$ decays

- Preliminary result using small fraction of 2016 statistics ($1.5 \cdot 10^{10}$ K decays)
- 90% CL upper limits statistically compatible with fluctuations in background-only hypothesis
- Full 2016 analysis in progress
Visible dilepton final states

90% CL expected UL for $10^{18}$ pot (on Be target) using both final states and in zero-background assumption

Sensitivity does not include $A'$ production in dump and QCD contributions.
**Dark scalar**

- Simplified model with $\lambda=0$ assumed (single scalar)
- $10^{18}$ pot assumed
- $e\mu, \pi\pi, \text{KK final states}$
- 90% CL UL sensitivity w zero-bkg assumption

\[ L_{\text{scalar}} = L_{\text{SM}} + L_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H \]

\[ L_{\text{DS}} = S\bar{\chi}\chi + \ldots \]

\[ \theta = \frac{\mu\nu}{m_h^2 - m_S^2} \]

**NA62 estimated sensitivity for $10^{18}$ pot**

Data from 2016-2017 runs:
- $3 \cdot 10^{17}$ pot in $\mu\mu$
- $5 \cdot 10^{16}$ pot in $ee$
Axion Like Particles

- Axions may solve the strong CP problem while providing a light DM candidate.
- At NA62: $\gamma\gamma$ fusion via Primakoff effect for production and subsequent $\gamma\gamma$ decay
- Need beam-dump mode (closed TAXES)
- Significant result already w $10^{16}$ pot.
- Analysis of $5 \cdot 10^{15}$ pot collected in dump mode in 2017 in progress.
- Sensitivity (90% CL UL) estimate for $10^{18}$ pot in dump mode. Zero-bkg assumption.
3 RH neutrino model could explain neutrino mass hierarchy, DM and barion asymmetry [Asaka, Shaposhnikov PLB 620 (2005) 17].

HNL are expected to couple w ordinary SM leptons

Na62 search for HNL with Minimum Bias data collected in 2015 ($10^8$ kaon decays)

Search for HNL in both eN and μN final states

Long lived N → invisible decays

Search for missing mass peaks on smooth polynomial background.
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Best world limit above 300 MeV/c^2

Full 2016-2018 data set analysis ongoing
Heavy neutral leptons from dump

- N produced in beam dump
- Two-track final states detected
- Assume $10^{18}$ pot on TAXES and zero-bkg
- 90% CL upper limit
- 3 scenarios as in Gorbunov, Shaposhnikov JHEP 10(2007)015

$U_e^2:U_\mu^2:U_\tau^2 = 52:1:1$
Normal hierarchy of active $\nu$ masses

$U_e^2:U_\mu^2:U_\tau^2 = 1:16:3.8$
Normal hierarchy of active $\nu$ masses

$U_e^2:U_\mu^2:U_\tau^2 = 0.061:1:4.3$
Normal hierarchy of active $\nu$ masses

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Conclusions and perspectives

- NA62 is very well suited to explore the low mass, low coupling region in several NP scenarios.
- Analysis is in progress on 2016-2018 data for both kaon decays and target/dump production modes.
- Possibility to collect $10^{18}$ pot in dump mode in 2021-2023 to fully exploit the NA62 potential for searches and limits.
Additional material
The zero background assumption

- Zero bkg assumed to obtain expected sensitivities for visible modes.
- Checks have been done for $\mu^+\mu^-$ final state at low statistics ($10^{15}$ pot) where no signal is expected and $\mu^+\mu^-$ combinatorial background dominates
- No event survived selection
NA62 beyond LS2

Run 3: many interesting fields to be studied with minimal (or no upgrades at all) of the existing setup

- In $K^+$ beam mode:
  - If needed improve $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $A' \rightarrow$ invisible, invisible HNL
    - All benefit from the same trigger signature

- In proton beam dump mode:
  - ALPs, Dark scalar, $A'$, HNL: all in visible decays

1 year of data taking in beam dump mode during Run 3 is under consideration
What about $K^+ \to \pi^+ \nu\bar{\nu}$?

- First results on 2016 data
- Expected 0.27 SM events and 0.15 bkg events
- 1 signal candidate observed

Results (published soon) →

- $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10}$ @ 68% CL

Current best result from E787/949 at BNL (@ 68% CL)

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$