Search for exotic decays in NA62

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Outline

• The NA62 experiment at the CERN SPS

• NA62 exotics searches:
  − Heavy Neutral Lepton (HNL) searches
  − Dark Photon (DP) searches
  − Future prospects

• Summary
The NA62 experiment

**NA62** – fixed target kaon experiment at CERN SPS

**Main goal**: measurement of the BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) with 10% precision using novel *kaon-in-flight* technique.

**Theoretical prediction:**

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

[Buras et al., JHEP11(2015)033]

**Experimental result before NA62:**

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


**Broader physics program:**

- Rare/forbidden kaon decays
- Searches for exotic processes

~30 institutes, ~200 participants from:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC
Detector overview

Performances:
- GTK-KTAG-RICH time resolution: $O(100 \text{ ps})$
- $O(10^4)$ background suppression from kinematics
- $O(10^7)$ muon rejection for $15 < p(\pi^+) < 35 \text{ GeV}$
- $O(10^8)$ $\pi^0$ rejection of for $E(\pi^0) > 40 \text{ GeV}$
Time scale:
2014 – Pilot run
2015 – Commissioning run: ~1% of design intensity, no beam tracker
2016 - Commissioning run + Physics run (30 days)
2017 – Physics run (161 days)
2018 – Physics run (217 days)
2019-2020 – LS2
HNL searches in kaon decays

\[
\Gamma(K^\pm \to l^\pm N) = \Gamma(K^\pm \to l^\pm \nu_l) \rho(m_N) |U_{l4}|^2
\]

- HNL production is enhanced wrt SM decays
- Large \( f \sim 10^5 \) enhancement in the \( K^+ \to e^+N \) case: helicity suppression is relaxed.

Kinematic factor

\[
[\text{R. Shrock PLB96 (1980) 159}]
\]

\[
R_K \approx 2.5 \times 10^{-4}
\]

\[
\rho_\mu(m_N)
\]

\[
\rho_\epsilon(m_N) \cdot R_K
\]

\[
m_{N}, \text{GeV/c}^2
\]
HNL searches in kaon decays

- **Data:** 2016+2017 for muon mode and 2017+2018 for positron mode
- **Triggers used:** the main $K_{\pi\nu}$ for $K^+\rightarrow e^+N$; **Control** (min bias)/400 for $K^+\rightarrow \mu+N$.
- Numbers of $K^+$ decays in the fiducial volume: $N_K=(3.52\pm0.02)\times10^{12}$ in **positron** case; $N_K=(4.29\pm0.02)\times10^{9}$ in **muon** case.
- **Peak searches in the squared missing mass:** $m_{\text{miss}}^2=(P_K-P_\ell)^2$, where $P_K$ is kaon 4-momentum measured using GTK, and $P_\ell$ is lepton 4-momentum measured using STRAW.
**HNL production search summary**

- No HNL signal was observed
- Full data set for positron mode and \( \sim 1/3 \) of the data set for muon mode.
- Improvements over earlier production searches by up to 2 order of magnitude
- Muon case: sensitivity approaches E949. Search extends to 383 MeV/c\(^2\)
- Positron case: the BBN-allowed range is excluded up to 340 MeV/c\(^2\)
Dark photon searches in $\pi^0$ decays

Dark photon produced in $\pi^0$ decay via kinetic mixing $\epsilon$ with SM photon $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow A'\gamma$:

$$\mathcal{B}(\pi^0 \rightarrow \gamma A') = 2\epsilon^2 \left( 1 - \frac{m_{A'}^2}{m_{\pi^0}^2} \right)^3 \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$$

where $A' \rightarrow$ invisible or long lived

- **Data:** 5% of 2016 data (1% of full available statistics)
- **Trigger:** main $K_{\pi\nu\nu}$ trigger
- **Selection:** Tag $\pi^0$ of known momentum from $K^+ \rightarrow \pi^+\pi^0$ and select events with $\pi^0 \rightarrow \gamma + $ invisible
- **Peak searches in the missing mass spectrum:** $m^2_{\text{miss}} = (P_K - P_{\pi} - P_\gamma)^2$

![Diagram of particle interactions and mass spectrum](image)
Dark Photon – 2016 result

- No DP signal was observed
- Improved limits on $\epsilon^2$ in 60-110 MeV/c$^2$ range (already covered by NA64 [PRL 123, 121801])
- Set 3 orders of magnitude better upper limits on:
  $$\mathcal{B}(\pi^0 \rightarrow \gamma\nu\bar{\nu}) < 1.9 \times 10^{-7}$$
Future prospects: NA62++

- The NA62++ experiment uses the same NA62 apparatus in a “beam dump” mode
  - NA62++ can collect $O(10^{18})$ protons on target (POT) in $O(3)$ months
  - Possibility to run in this mode in 2023

- The physics prospects of NA62++ have been studied as part of the ‘Physics Beyond Colliders – Beyond the Standard Model’ working group [arxiv:1901.09966]

- The following slide shows NA62++ prospects assuming $O(10^{18})$ POT and negligible background

- The limits are set at 90% CL

Note:

- The results of studies based on $O(10^{16})$ POT show negligible background level
- A detailed, G4-based MC simulation developed within the PBC reproduces the distribution of single-track background events
- Improvements to the NA62++ setup (upstream veto, beamline modifications, higher intensity) are not included here, but initial studies are promising
HNL decay searches

- HNL decay searches to visible final states with at least two charged tracks, where HNL produced in leptonic decays of B and D mesons

- Expected sensitivity in the plane HNL coupling to one SM generation vs HNL mass
  - account for acceptance
  - zero-background assumption

Dark photon decay searches

- Decay searches for $A' \rightarrow ll$
- Expected sensitivity in the plane $A'$ mixing with SM photons vs $A'$ mass:
  - account for geometrical acceptance
  - zero-background assumption
- Sensitivity expected to be higher than shown:
  - including direct QCD production of $A'$
  - Including $A'$ production in the collimator (here, only target)

ALP decay searches

- Decay searches for $a \rightarrow \gamma\gamma$, where $a$ produced via elastic scattering of beam proton dumped onto collimator material.
- Analysis of 2017-2018 data is ongoing ($2 \times 10^{16}$ POT) – first results are expected very soon!
- Expected sensitivity in the plane ALP coupling to photons vs ALP mass:
  - account for geometrical acceptance
  - zero-background assumption

Summary

- The NA62 experiment is a powerful laboratory to make searches for exotic particles in both production and decay modes:
  - Final upper limits on HNL mixing parameters in positron case and preliminary upper limits in the muon case
  - Preliminary new limit on dark photon coupling
  - Further results and useful studies will be obtained with the NA62 full data set analysis (2016-2018)

- 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 Heavy neutral leptons (HNL), dark photons (A’), and axion-like particles (ALP)
Thank you!
[Backup slides]
Beam dump mode of NA62

Beam dump mode of NA62

Normal data taking

BD mode

400 GeV/c protons

75 GeV/c K^+, π^+, etc...

Target

400 GeV/c protons

[Target is removed!]

proton beam

[Target is removed!]

proton beam

[Copper collimator closed (TAXes) = dump]

65m decay region, 10^{-6} mbar vacuum

X [m]

-2

-1

0

1

2

Y [m]

0

100

150

200

250

Z [m]
HNL production searches: mass resolution

- “mass window” for the mass scan procedure: $|m-m_N|<1.5\sigma_m$: background is proportional to mass resolution.
Mass scan procedure

- HNL mass range: 141–462 (220–383) MeV/c^2 in the Ke_2 (K\mu_2) case.
- Scan step:
  - \sigma_m/2 in the Ke_2 case;
  - 1 (0.5) MeV/c^2 below (above) m_N=300 MeV/c^2 in the K\mu_2 case.
- Number of mass hypotheses tested: 264 (247) in the Ke_2 (K\mu_2) case.
- Signal region half-width: 1.5\sigma_m.
- In each mass hypothesis m_0, background (and its stat. error) determined from the data (polynomial fits in sidebands: approx 1.5\sigma_m<|m-m_0|<12\sigma_m).
- Limits on |U\ell4|^2: CL_S comparison of observed vs expected event counts.
HNL production searches: ULs on numbers of signal events, 90%CL

\( K^+ \rightarrow e^+\nu \)

\( K^+ \rightarrow \mu^+\nu \)

Number of events

Number of signal events

Squared HNL mass [GeV^2/c^4]

HNL mass hypothesis [MeV/c^2]
HNL production searches:
ULs on BR(K→ l^+N), 90%CL

- Maximum local significance $3.6$ for $m_N=346\text{MeV/c}^2$
- Global significance: $2.2$
Dark Photon – NA64
Future prospects 10-15 years scale

**Coupling to SM photon**

\[ a \rightarrow \gamma\gamma \]

**Mixing with SM photon**

\[ A' \rightarrow ll \]

**Mixing with SM Higgs**

\[ S \rightarrow ll \]

**Electron coupling dominant**

**Muon coupling dominant**

**Tau coupling dominant**

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