Search for heavy neutrinos at CERN SPS

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The phenomenology in the neutrino sector requires physics beyond the Standard Model. One possibility is the existence of new massive leptonic states which could be probed at the high intensity machines. The present results on heavy neutral leptons from the study of kaon decays in flight with the NA48/2 and NA62 experiments are presented and the future prospects for such searches at CERN SPS are discussed.

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1 Introduction

A possible explanation of the neutrino oscillations is the extension of the Standard Model with three sterile Majorana neutrinos $N_i$ - the so called Neutrino Minimal Standard Model ($\nu$MSM)\cite{1}. The mass of the lightest neutrino could be of the order of 1 keV/c$^2$, making it a suitable Dark matter candidate, while the mass of the others could be in the range from 100 MeV/c$^2$ to few GeV/c$^2$. The observed small masses of the left handed neutral leptons are provided through the see-saw mechanism. The ($\nu$MSM) could also be extended by a scalar field $\chi$ to account for the inflation $\cite{2}$.

In meson decays, the heavy neutrinos are produced through mixing with the ordinary ones. For example, the rate for the decay $K^+ \rightarrow \ell^+N$ is given by $\cite{3}$

$$\Gamma(K^+ \rightarrow \ell^+N) = \Gamma(K^+ \rightarrow \ell^+\nu) \times \rho_\ell(m_N) \times |U_{\ell4}|^2, \quad (1)$$

where $m_N$ is the heavy neutral lepton (HNL) mass, $|U_{\ell4}|$ is the mixing parameter between the HNL and the neutrino corresponding to the lepton $\ell$, and $\rho_\ell(m_N)$ is a kinematic factor which includes also the helicity suppression in the electron case. $\rho_\ell(m_N)$ is $O(1)$ for most of the accessible $m_N$ range.

The decay width of the HNL is proportional to $|U_{\ell4}|^2 \times m_N^3$. Depending on its mass and mixing, different scenarios are possible:

- HNL decays within the fiducial region of the experiment. For $m_N < 500$ MeV/c$^2$ the possible final states are $N \rightarrow \pi^0\nu$, $N \rightarrow \pi^\pm\mu^\mp$, $N \rightarrow \pi^\pm\epsilon^\mp$, $N \rightarrow \nu\nu\nu$.

- If $|U_{\ell4}|^2 < 10^{-4}$ then $\gamma c\tau_N > 10$ km and $N$ could be considered invisible to the experimental apparatus.

The presence of Majorana mass term could manifest itself in the Lepton Number Violating decay (LNV) $K^\pm \rightarrow \pi^\pm\mu^\mp\mu^\pm$. In addition, the existence of a heavy neutrino with $2m_\mu < m_N < m_{K^\pm} - m_{\pi^\pm}$ might appear as a resonance in the $M_{\pi\mu}$ mass spectrum of the Lepton Number Conserving (LNC) decay $K^\pm \rightarrow \pi^\pm\mu^\mp\mu^\mp$.

2 Exclusive HNL searches

A search for the decay $N \rightarrow \pi^\pm\mu^\mp$ of a HNL produced in $K^+ \rightarrow \ell^+N$ has been performed by both NA48/2 and NA62 experiments.

NA48/2 operated in 2003 and 2004 with simultaneous $K^+$ and $K^-$ beams with $(60 \pm 3.7)$ GeV/c momentum. The kaon decay products were registered by the NA48 detector $\cite{4}$. A spectrometer consisting of four drift chambers separated by a dipole magnet measured the momentum of the charged particles with resolution $\sigma(p)/p = (1.0 \pm 0.044 \ p [\text{GeV/c}])\%$. The timing and a fast trigger condition were provided by a scintillator hodoscope with time resolution of 150 ps. The energy of photons
and electrons was measured by a quasi-homogeneous liquid krypton electromagnetic calorimeter, providing resolution $\sigma(E)/E = 3.2%/\sqrt{E} \oplus 9%/E \oplus 0.42\%$ (energy is in GeV). The charged particle identification was based on the ratio $E/p$.
of the kaon momentum, flight direction, and time. A set of scintillating counters, CHANTI, provide a veto against interactions of the beam particles. The beam enters a 75 m long evacuated fiducial volume, followed by a spectrometer with a minimal material budget. It is made of four chambers of straw tubes operated in vacuum and separated by the MNP33 dipole magnet. A fast plastic scintillator charged hodoscope is used in the trigger. The NA48 liquid krypton calorimeter with renewed readout electronics measures the energy deposited by the particles and also serves as a photon veto for photons with angles from 1.5 to 8.5 mrad with inefficiency less than $10^{-5}$ for photons with energy above 10 GeV. Twelve rings of lead glass counters surrounding the decay region act as photon vetos for angles of the photons higher than 8.5 mrad with respect to the kaon flight direction. They are accompanied by two shashlyk type detectors covering photon angles down to zero. The $\pi/\mu$ separation is based on the information from a neon filled ring imaging Cherenkov detector, measuring the velocity of the charged particles, and three stations of muon detectors. Both KTAG and Gigatrack are exposed to the full 750 MHz hadron beam while the particle rate seen by the downstream detectors is at most 10 MHz. The high kaon flux combined with precise kinematics measurement, particle identification, and hermeticity make the NA62 detector extremely powerful for the study of rare processes with kaons.

Using a partial dataset, a search for the LNV modes $K^+ \rightarrow \pi^- \ell^+ \ell^+$, both for $\ell = \mu, e$, was performed within NA62. The obtained invariant mass spectrum for the LNC modes $K^+ \rightarrow \pi^+ \ell^+ \ell^-$, which are used for normalization, is shown in fig. 3. The $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ sample is the world largest one, while the $K^+ \rightarrow \pi^+ e^+ e^-$ analysis allowed the first observation of the decay in the mass range $m_{ee} < 140$ MeV/c$^2$. The NA62 detector was fully operational during the 2017 and 2018 data taking and major improvements in the exclusive search for HNL is expected. The single event sensitivity for the LNV modes is estimated to be $SES \sim 10^{-10}$ both for the electron and muon mode due to the negligible expected background.
Inclusive HNL searches

Inclusive search for HNL can be performed by looking for “bumps” in the missing mass spectrum of the $K^\pm \to \ell^\pm X$ decays, $|m_{\text{miss}}|^2 = (P_K - P_\ell)^2$, with the charged lepton being the only reconstructed particle in the final state.

During the early stage of NA62, a large data sample of $K^+$ decays was collected in 2007 with a minimum bias trigger devoted to the measurement of $R_K = \Gamma(Ke\bar{\nu})/\Gamma(K\mu\nu)$ and the test of the lepton universality [8]. The nominal kaon momentum was 75 GeV/c and the MNP33 current was increased to provide a $p_T$ kick of 265 MeV/c, leading to momentum resolution of $\sigma(p)/p = (0.048 \oplus 0.009)\%$. The nominal $P_K$ was calculated from $K_3\pi$ events. The search for peaks was performed in the muon channel, in the mass range $300 \text{ MeV}/c^2 < m_{\text{miss}} < 375 \text{ MeV}/c^2$ with a step of 1 MeV/c$^2$. The dominant background was from $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu(\gamma)$ decays and from the muon halo. No signal exceeding 3$\sigma$ above the expected background was observed. The Rolke-Lopez method was applied and an upper limit on $Br(K^+ \to \mu^+ N)$ was obtained [9].

Using 5 days of data, recorded in 2015 with beam intensity corresponding to 1% of the nominal and a minimum bias trigger, the NA62 experiment performed a search for HNL in the missing mass spectrum both for the electron and the muon mode [10]. The already developed technique for the analysis of 2007 data was applied. The charged lepton momentum had to be between 5 GeV/c and 70 GeV/c. The search region for HNL was chosen to be $170 \text{ (250) MeV}/c^2 < m_{\text{miss}} < 448 \text{ (373) MeV}/c^2$ for the electron (muon) channel. MC simulation was used to obtain the resolution $\sigma(m_N)$ and to calculate the acceptance for $K^+ \to \ell^+ N$ events as a function of the HNL mass.
Figure 4: Upper limits on the branching fraction for the $K^+ \to \ell^+ N$ (left) and the obtained upper limits on the mixing parameter $|U_{\ell 4}|^2$ (right) as a function of the heavy neutrino mass. Data from previous experiments is also shown for comparison.

The maximum value of the local signal significance $z = (N_{\text{obs}} - N_{\text{exp}}) / \sqrt{N_{\text{obs}} + \delta N_{\text{exp}}^2}$ was 2.2, obtained for $m_N = 283$ MeV/c$^2$ in the electron channel. The normalization was based on the reconstruction of the corresponding $K^+ \to \ell^+\nu$ decay and was used to obtain an upper limit on the branching fraction for the $K^+ \to \ell^+ N$ decays, shown in fig. 4-left. These upper limits on BR were translated into upper limits on the mixing parameters $|U_{e4}|^2$ and $|U_{\mu4}|^2$, shown in fig. 4-right.

As in the exclusive search case, a major improvements on the presented results could be expected with the present NA62 data.

4 Future facilities

The sensitivity of the presented searches at CERN SPS is limited by the statistics of the produced mesons, which afterwards may decay to final states with HNLs. This limitation could be overcome by entirely absorbing the primary proton beam and most of its interaction products in a thick target, a technique known as beam-dump. The outgoing beam from the target consists of long lived neutral particles which enter a decay region.

The number of the expected HNL in the detector is a product of the produced HNLs and the probability for their observation [11]. The possible source of HNLs are the (semi)leptonic decays of $\pi$, $K$, $D$, and $B$ mesons and the produced number of HNLs depends on the production of a given quark flavour in the target, its probability to hadronize to a certain meson and to decay to final states with HNL. The detection
probability is given by

$$P_{det} = \left[ e^{-\frac{l_{ini}}{\tau}} - e^{-\frac{l_d}{\tau}} \right] \times BR(N \to \text{visible}) \times \epsilon_{det}$$

(2)

and depends on the length of the setup $l_{ini}$ before the decay region, the length of the decay region $l_d$, the lifetime $\tau$ of the HNL, the visible branching fraction and the corresponding acceptance $\epsilon_{det}$.

The description of two selected facilities, a short term one (within 5 years) and a long term (10-15 years) one, discussed also within the Physics Beyond Coliders initiative \[12\], follows.

### 4.1 NA62 in beam dump mode

The NA62 beryllium target is followed by two $\sim 11$ nuclear interaction length water cooled copper-steel collimators (TAX) to stop the residual proton beam from SPS. The dump mode operation could be provided by closing the first TAX. This allows to exploit the particle identification, tracking, and hermeticity of NA62 to search for long lived neutral particles, including HNL. The goal is to collect $O(10^{18})$ POT in RUN3 \[13\].

![Figure 5: Expected sensitivity of NA62 in beam dump mode (left) \[12\] and SHiP (right) \[11\] to the mixing parameter $|U_{\mu}|^2$ as a function of the HNL mass. Filled area is excluded by theory or previous experiments.](image)

The projected sensitivity of NA62 in beam dump mode (90% CL upper limit) for the case of dominant mixing with the second generation ($|U_e|^2 : |U_\mu|^2 : |U_\tau|^2 = 0 : 1 : 0$) is shown in fig. 5-left. It was obtained assuming zero background and the possibility to detect all two-track final states. The geometrical acceptance and the trigger efficiency were taken into account.

About $3 \times 10^{16}$ POT have been collected by NA62 in a dedicated beam dump mode. No background was achieved for fully reconstructed final states. Additional samples collected in the presence of kaon beam are currently being used for dimuon background studies.
4.2 SHiP

The Search for Hidden Particles (SHiP) experiment, shown schematically in fig. 6, aims to collect $2 \times 10^{20}$ protons on target in 5 years of data taking. It exploits a general purpose beam dump facility to complement the existing LHC programme in the search for New physics.

The primary proton beam from SPS interacts in a very dense target ($11 \lambda_I$) followed by an hadron absorber. This assures abundant production of heavy flavour states and also effectively stops the secondary protons and kaons. The target region is followed by an active muon shield to deflect the muons. The neutron interactions are reduced by evacuating the 60 m long decay region. The decay products are measured by a downstream magnetic spectrometer with large acceptance. A particle identification system is also foreseen.

Figure 6: SHiP experimental setup.

The estimated sensitivity (90 % confidence region) to HNL are obtained under the zero background assumption. The production fraction of $B_c$ mesons is unknown at SPS energies [14] and is part of the systematic uncertainty. For the case of mixing with the second generation only the SHiP sensitivity is shown in fig. 5-right. A region up to $m_N \sim O(6 \text{ GeV/c}^2)$ and $|U_{\mu}|^2$ down to $10^{-10}$ could be covered, complementing the possible reach with a Future Circular Colider (FCC) in $e^+e^-$ mode.

The activities on the design and the construction of the detectors for the SHiP experiment are ongoing and almost every component has achieved at least first stage of prototyping [15].

5 Conclusions

A diverse heavy neutral leptons search programme is being executed at CERN with the NA62 experiment, covering both exclusive and inclusive events reconstruction.
So far no signature of new states have been observed in the (semi)leptonic decays of $K^\pm$. The obtained results are improving the existing limits on the HNL mixing parameters in the considered mass range.

A possible increase of the sensitivity is related to the application of the beam dump technique. Beyond the $K^+ \to \pi \nu\bar{\nu}$ phase of NA62 experiment, NA62++ could collect $10^{18}$ POT in few months of operation during RUN3 (2021-2023). A dedicated beam dump facility with the SHiP experiment in the SPS North Area could further increase the statistics to $2 \times 10^{20}$ POT in 5 years of operation, starting during RUN4 (after 2027).

Both NA62++ and SHiP are part of the PBC working group and provide input to the European Strategy for Particle Physics.

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