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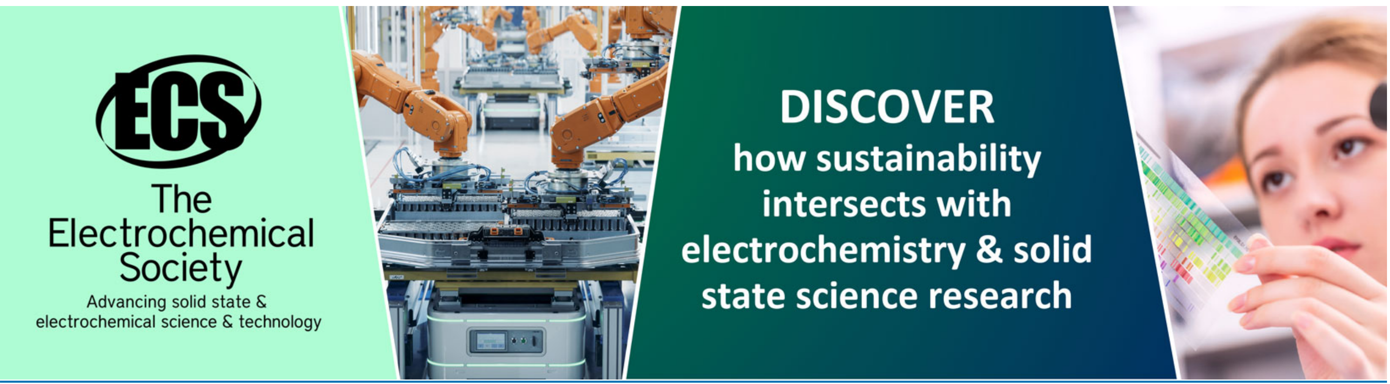

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Search for heavy neutral leptons with kaon experiments at CERN

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Abstract. Searches for heavy neutral leptons in charged kaon decays have been performed under different conditions by the NA62 and NA48/2 experiments at the CERN SPS. This paper describes the most recent results set by those experiments compared to previous measurements.

1. Introduction

Massive neutrinos are required by theoretical predictions beyond the Standard Model (SM) in order to accommodate the observation of neutrino oscillations. The Neutrino Minimal Standard Model (νMSM) [1][2] is a natural SM extension introducing the existence of three right-handed singlet heavy neutrinos (HNs) which mix with the standard ones and explain simultaneously neutrino oscillations, dark matter and baryon asymmetry in the Universe. The mixing of sterile and active neutrinos leads to the production of HNs in weak decays of hadrons and provides their decays to SM particles [3]. New results from HN searches in charged kaon decays, recently set by the NA62 and NA48/2 experiments at the CERN SPS, are summarized in this paper.

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2. HN searches in kaon decays

According to νMSM, HNs with mass m_N below the kaon mass can be produced through mixing between HNs and SM neutrinos in the leptonic kaon decays $K^{\pm} \to l^{\pm}N$ ($l = e, \mu$), where N is the new HN. The branching ratio (BR) of those decays depends on m_N and on the mixing parameter $|U_{l4}|^2$ and can be expressed in terms of the BR of the SM decay $K^{\pm} \to l^{\pm}\nu$ (K_{l2}) introducing a kinematic factor $\rho_l(m_N)$ accounting for helicity suppression and phase space dependence on m_N[4][5]:

$$BR(K^{\pm} \to l^{\pm}N) = BR(K^{\pm} \to l^{\pm}\nu) \times \rho_l(m_N) \times |U_{l4}|^2 \quad (1)$$

Limits on the mixing parameter for m_N below the kaon mass can be established by searching for resonances producing peaks in the missing mass spectrum of kaon leptonic decays.

The NA62 experiment at CERN and its predecessor NA48/2 performed complementary HN searches with charged kaon decays under different conditions.

2.1. NA48/2 results

NA48/2 took data in 2003 and 2004 with the main goal of searching for direct CP violation in 3-pion charged kaon decays [6]. Simultaneous K^+ and K^- beams were produced by 400 GeV protons from CERN SPS impinging on a Be target. Details of the experimental apparatus can be found in [7]. The experiment collected the largest world sample of charged kaon decays.

Search for production and decay of HN into pairs of opposite-charge particles has been exploited studying events with three tracks in the final state [8]. The analysis was performed on 2×10^{11} kaon decays. Samples of $K^{\pm} \to \pi\mu\mu$ decays have been selected looking for short lived sterile neutrinos N produced in $K^{\pm} \to \mu^{\pm}N$ transitions and promptly decaying into pion-muon pairs according to $N \to \pi\mu$. A peak in the invariant mass distribution of the pion-muon system could reveal the existence of the sterile neutrino N. A statistical analysis has been performed and the significance of the signal does not exceed 3 standard deviations in any mass bin. Upper limits of O($10^{-4} \div 10^{-5}$) have been set on the squared mixing parameter $|U_{\mu4}|^2$ as a function of the HN mass and lifetime. Those results are valid for unstable HNs with lifetime τ <100 μs.

2.2. NA62 results

NA62 is the last generation kaon experiment at the CERN SPS. It aims to measure the BR of the ultra-rare $K^+ \to \pi^+\nu\overline{\nu}$ decay with 10% accuracy. The SM calculation of this BR is of O(10^{-10}) with very small uncertainty [9], therefore its precision measurement is a remarkable test of the SM flavour sector. The NA62 strategy requires a high kinematic rejection power, an effective photon and muon reduction and excellent particle identification, in order to suppress background channels with BR up to 10 orders of magnitude higher than the signal.

In 2007 NA62 took data at an early stage, exploiting an experimental apparatus based on the NA48/2 detector and beam line optimized to improve the collection of electrons and muons in the final states. The main goal at that time was to test lepton flavor universality by measuring the ratio of the widths of charged kaon leptonic decays R_K=$\Gamma(K_{e2})/\Gamma(K_{\mu2})$ [10].

Since 2015 NA62 is taking data with a completely renovated beam line and experimental apparatus [11] specially designed for the precision measurement of BR($K^+ \to \pi^+\nu\overline{\nu}$).

The NA62 experiment, approved for running until the year 2018, exploits a positive charged hadron beam with 75 GeV/c momentum and 1% r.m.s. spread, produced by SPS proton interactions with a Be target. The nominal instantaneous beam particle rate is 750 MHz, due to π^+ (70%), protons (23%) and K^+ (6%). About 13% of the kaons decay in the fiducial volume, leading to 5 MHz nominal K^+ decay rate. A muon flux (beam halo) of 3 MHz nominal rate in the detector acceptance is produced by kaon and pion decays upstream of the vacuum tank. Beam kaons are tagged by a differential Cherenkov counter with nitrogen radiator (KTAG). Beam particle momenta are measured by a silicon pixel detector (GTK) under commissioning in 2015 and, therefore, not used in the 2015 data analysis. A 75 m long fiducial decay volume in vacuum follows the last GTK station. A spectrometer, made of four chambers with straw tubes in vacuum and a dipole magnet, measures track directions and momenta in the decay region. Among the decay products, pions and muons are distinguished by a ring imaging Cherenkov detector filled with neon gas and by muon detectors. A system of calorimeters detects photons at different polar angles from the beam axis.

Only HN production in kaon leptonic decays has been investigated in NA62 due to the fact that, assuming $|U_{\mu 4}|^2 < 10^{-4}$ and HN decays into SM particle, the expected mean free path of HNs is above 10 Km and the decay probability in the NA62 fiducial volume is negligible.

In 2007 NA62 collected $N_K = (5.977 \pm 0.015) \times 10^7$ K^+ and K^- decays. Due to a smaller muon halo background contamination in the K^+ sample, HN production has been studied in $K^+ \to \mu^+ N$ transitions [12]. Resonances in the m_{miss} spectrum are the expected signal signature. A search for peaks in the m_{miss} distribution has been performed in steps of 1 MeV/c^2. The Rolke-Lopez statistical method has been applied in each m_{miss} bin to find the 90% confidence intervals for a poissonian process with gaussian background. No significance above 3 sigma has been found. Upper limits of O($10^{-5} \div 10^{-6}$) at 90% $C.L.$ on the squared mixing parameter $|U_{\mu 4}|^2$ as a function of the HN mass in the mass signal region 300−375 MeV/c^2 have been evaluated from those set on the BR according to equation (1).

In 2015 NA62 has investigated HN production in $K^+ \to l^+ N$ ($l = e, \mu$) leptonic decays with data collected at 1% of the nominal beam intensity in a special minimum bias run. Both muon and electron final states have been studied [13]. The $K^+ \to l^+ N$ decay rates have been measured with respect to those of the normalization SM channel $K^+ \to l^+ \nu$, with similar topologies and known branching fractions. The $K^+ \to l^+ N$ decay is characterized by a single track detected in the final state, similarly to the SM $K^+ \to l^+ \nu$ one. Single positively-charged tracks within the detector acceptance, with momenta between 5 and 70 GeV/c, are selected in the spectrometer. No detector activity or additional tracks in time with the selected ones are allowed. A well reconstructed kaon decay vertex is required. A kaon signal in the KTAG and strict geometrical conditions on the kaon decay vertex position in the upstream part of the detector, close to the beginning of the fiducial decay region, are also required in order to suppress beam halo background from K^+ decays upstream of the last GTK station. Being commissioned in 2015, the GTK beam tracker is not used in this analysis. Pion and muon identification is achieved by exploiting the muon veto detector information and the energy deposited in the LKr calorimeter compared with the momentum measured by the spectrometer. The squared missing mass $m^2_{miss} = (P_K - P_l)^2$, given by the lepton and kaon 4-momenta, is computed with the lepton 3-momentum of the spectrometer track in the corresponding mass hypothesis and with the beam average 3-momenta monitored from reconstructed $K^+ \to \pi^+\pi^+\pi^-$ events. Particle interactions and detector response are reproduced with a Geant4 Monte Carlo (MC) simulation.

Figure 1 displays the m^2_{miss} spectra of the selected events from both data and simulation. Signals from the SM leptonic decays are observed as peaks at $m^2_{miss} = 0$ with m^2_{miss} resolutions of $4.9(4.7) \times 10^{-3}$ GeV^2/c^4 in the e^+ (μ^+) case. The expected numbers of signal events N^l_S depend on the assumed branching fractions BR($K^+ \to l^+ N$) and acceptances A^N_l of the selections according to $N^l_S = N^l_K \times BR(K^+ \to l^+ N)$, where N^l_K are the numbers of K^+ decays in the fiducial region computed from the numbers of selected data events with m^2_{miss} in the SM signal region. The search for HN in $K^+ \to e^+ N$ decays has been carried out in the mass signal region 170−448 MeV/c^2 on a number of $N^e_K = (3.00 \pm 0.11) \times 10^8$ kaon leptonic decays into electrons. A sample of $N^\mu_K = (1.06 \pm 0.02) \times 10^8$ kaon leptonic decays into muons have been analyzed to search for HN in $K^+ \to \mu^+ N$ transitions in the mass signal region between 250 and 373 MeV/c^2.

The HN search procedure is based on a data-driven background estimation method, only valid provided there are no peaking background structures in the HN mass region. Backgrounds to HN production, mostly given by K^+ decays, have been estimated by MC simulations to

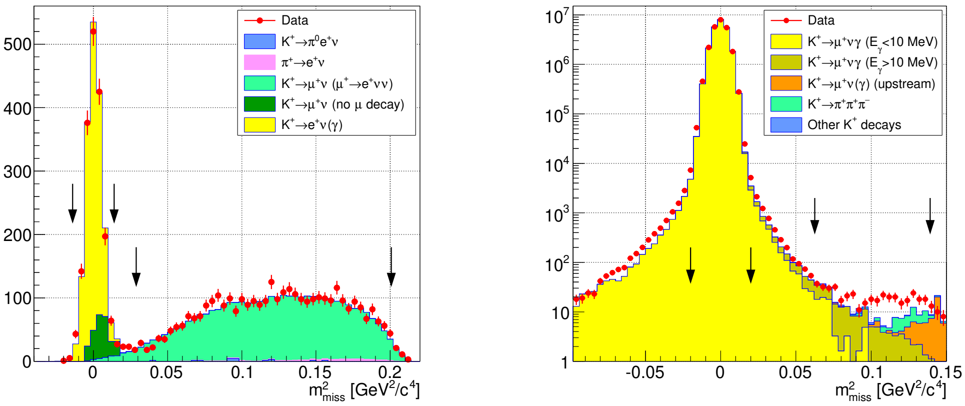

Figure 1. (Colours online) Distributions of m^2_{miss} for data and simulated events passing the (left) e^+ and (right) μ^+ selections (bin widths = 0.004 GeV^2/c^4). Pairs of vertical lines in each plot indicate the boundaries of the SM and HN signal regions. The HN signal regions correspond approximately to 0.03-0.20 GeV^2/c^4 and 0.06-0.14 GeV^2/c^4 in m^2_{miss} values in the e^+ and μ^+ case, respectively.

understand qualitatively their contributions and to optimize the event selection.

The main background contribution to $K^+ \to e^+N$ decays comes from the $K^+ \to \mu^+\nu$ decay followed by muon decay in flight $\mu^+ \to e^+\nu\nu$. Beam pion decays $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$ followed by muon decay in flight also contribute via π misidentification by the KTAG due to accidental coincidence with a beam kaon not decaying in the fiducial volume. The m^2_{miss} spectra of the estimated background components show good agreement with the data (see Figure 1).

The largest background component to $K^+ \to \mu^+N$ decays comes from $K^+ \to \mu^+\nu\gamma$ decays with photons outside the detector acceptance The m^2_{miss} spectra of the simulated background components in Figure 1 show marginal agreement with data. In the HN signal region, a background component with muons propagating close to the $y-z$ plane is observed in the data but not well reproduced with MC, due to the limited precision on the beam line simulation. The disagreement at negative m^2_{miss} is due to the limited precision of the m^2_{miss} resolution, affected by the simulation of the beam momentum spectrum and divergence.

A scan of the m^2_{miss} distributions is performed to search for peaks in the HN signal regions in steps of 1 MeV/c^2. A search windows size of $\pm$ 1.5 σ^l_m, where σ^l_m is the HN mass resolution evaluated with MC simulations (see Figure 2), is chosen for each HN mass hypothesis to optimize the expected upper limits on BR($K^+ \to l^+N$) in the absence of signals in the whole HN signal regions. The corresponding resolution on m^2_{miss} in the signal regions is a few 10^{-3} GeV^2/c^4 and has a weak mass dependence. In each HN mass hypothesis the total number of observed events within the $\pm$ 1.5 σ^l_m HN search window, the number of expected background events, evaluated from the sidebands of the m^2_{miss} data distribution, and its uncertainty, are used to compute confidence intervals for the number of observed $K^+ \to l^+N$ decays. The Rolke-Lopez statistical method has been applied in each mass bin to find the 90% confidence intervals for a poissonian process with gaussian background. The maximum value of the local signal significance is 2.2 for the e^+ case with m_N = 283 MeV/c^2. In the absence of statistically significant HN production signals, upper limits on the numbers of signal events and on BR($K^+ \to l^+N$) are established. The upper limits on the squared mixing parameter $|U_{l4}|^2$ are evaluated from those set on BR($K^+ \to l^+N$) according to equation (1). Figure 3 compares the upper limits on $|U_{l4}|^2$ at 90% $C.L.$ set by NA62 as a function of HN mass with the results from HN production searches in kaon[14][15] and pion[16][17] leptonic decays. The NA62 results improve existing limits on $|U_{e4}|^2$ over the whole mass range considered and above 300 MeV/c^2 on $|U_{\mu4}|^2$.

Further improvements are expected from the analyses of 2016, 2017 and 2018 data. Larger

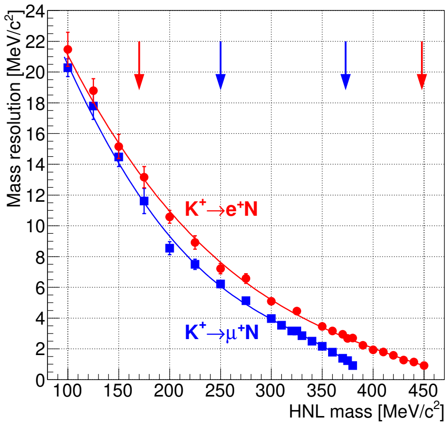

Figure 2. (Colours online) Missing mass resolution σ_m^l as a function of the HN mass from MC simulations with statistical errors and polynomial functions used to define the HN selection criteria. Vertical lines indicate the search regions.

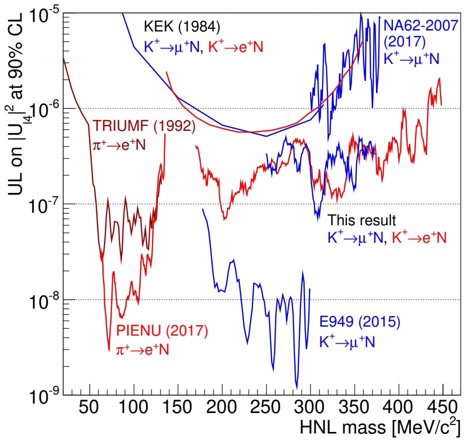

Figure 3. Upper limits (90% *C.L.*) on $|U_{l4}|^2$ ($l = e, \mu$) as a function of the HN mass: the NA62 results are compared with previous limits established in HN production searches.

data set have been collected due to higher beam intensity and longer running periods. Thanks to the GTK beam tracker operation a factor 2 improvement on HN mass resolution and a broader mass range will be accessible, a lower background from muon decays in flight (factor 3 reduction) and from upstream kaon decays will be achieved. With the analysis of the full NA62 data sample sensitivities better than 10^{-8} are expected for both the $|U_{e4}|^2$ and $|U_{\mu4}|^2$ measurements.

3. Conclusions

Searches for new particles beyond the SM predictions at NA62 benefit from the size of the data sample, the excellent resolution on kinematic variables granted by the low material budget of the NA62 detector, the effective particle identification and the photon veto capability. Further improvements of the NA62 searches on HN are expected soon from the analysis of the full data statistics. By the end of the run the NA62 limit on the mixing parameters from HN production searches below the kaon mass are expected to decrease by two orders of magnitude.

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