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New Limits on Heavy Neutrino from NA62

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The NA62 experiment at CERN collected large samples of charged kaon decays in flight with a minimum bias trigger configuration in 2007 and in 2015 using a completely new detector setup. Upper limits on the rate of the charged kaon decay into a muon and a heavy neutral lepton (HNL) obtained from 2007 data and limits for the charged kaon decay into an electron and a HNL obtained from 2015 data, are reported in this proceedings.

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Introduction

The Standard Model (SM) of particle physics cannot accommodate experimental data on neutrino oscillations because neutrinos are strictly massless in the SM and thus do not oscillate. The simplest renormalizable extension of the SM, consistent with neutrino experiments, involves the inclusion of heavy neutrinos, also called heavy neutral leptons (HNLs), which mix with ordinary neutrinos to explain several open questions. An example of such a theory is the Neutrino Minimal Standard Model (νMSM) [1]. In this model, three massive right-handed neutrinos are introduced to explain neutrino oscillations, dark matter and baryon asymmetry of the Universe. The lightest of these HNLs with the mass of $\mathscr{O}(1\,\mathrm{keV}/c^2)$ is a dark matter candidate, the other two, with the masses of $\mathscr{O}(1\,\mathrm{GeV}/c^2)$ generate the masses of the SM neutrinos via see-saw mechanism and introduce extra CP violating phases to account for baryon asymmetry.

The mixing between HNLs and the SM neutrinos leads to the HNL production in meson decays, such as $K^+ \to \ell^+ N$ $(\ell = e, \mu)$. The branching fraction of these decays is determined by the HNL mass m_N and the mixing parameter $|U_{\ell 4}|^2$ [2, 3]:

$$\mathscr{B}(K^+ \to \ell^+ N) = \mathscr{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2, \tag{1}$$

where $\mathscr{B}(K^+ \to \ell^+ \nu)$ is the branching fraction of the SM leptonic decay ($K_{\ell 2}$), and $\rho_\ell(m_N)$ is a kinematic factor accounting for the phase space and the helicity suppression. Numerically, the product $\mathscr{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N)$ is $\mathscr{O}(1)$ over most of the allowed m_N range.

Production of HNLs in $K^+ \to \ell^+ N$ decays can be searched for by looking for peaks in the missing mass spectra of the $K_{\ell 2}$ candidates. This proceedings summarizes results of two such searches from the NA62 experiment at CERN; a $K_{\mu 2}$ decay spectrum analysis using the data collected by NA62 in 2007 [4] and a preliminary result of a K_{e2} decay spectrum analysis using the data collected by NA62 in 2015.

1. Analysis overview

1.1 NA62 Experiment in 2007

The NA62 experiment is the successor to the NA48 series of kaon decay in-flight experiments at CERN. In its first phase of data taking in 2007, a modified beam line and the detector of NA48/2 were used for the measurement of the ratio $R_K = \Gamma(K^\pm \to e^\pm \nu)/\Gamma(K^\pm \to \mu^\pm \nu)$ [5].

The beam kaons with central momentum $74\,\mathrm{GeV}/c$ and momentum spread of $\pm 1.4\,\mathrm{GeV}/c$ decayed in a fiducial decay volume contained in a 114 m long cylindrical vacuum tank. The momenta of charged decay products were measured in a magnetic spectrometer, housed in a tank filled with helium placed after the decay volume. The spectrometer comprised four drift chambers (DCHs) and a dipole magnet. A plastic scintillator hodoscope (CHOD), placed after the spectrometer, produced fast trigger signals and provided precise time measurements of charged particles. A liquid krypton electromagnetic calorimeter (LKr), an iron/scintillator hadronic calorimeter and muon detectors (MUV) were located further downstream. A detailed description of the beam line and the detector can be found in [6, 7].

The beam intensity of NA62 in 2007 was reduced compared to NA48/2 by a factor of ~ 10 to enable the operation of a minimum bias trigger configuration with high efficiency, and to minimize the accidental background. The main trigger condition for selecting the sample of $K^+ \to \mu^+ \nu$ decay candidates required a signal in the CHOD detector with loose lower and upper limits on the DCH hit multiplicity, downscaled by a factor of 150.

1.2 NA62 Experiment in 2015

The main goal of the NA62 experiment is the measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay branching fraction with 10% precision. The NA62 experiment uses high energy protons from the SPS (400 GeV/c) to produce a secondary hadron beam (6% kaons) of momentum (75 ± 1.0) GeV/c and the nominal intensity of 750 MHz. The experimental setup extends from the beryllium target to the beam dump over a distance of about 270 m, see Figure 1. The main improvements with respect to the 2007 setup include the tagging and the time measurement of individual kaons in the beam by the KTAG Cherenkov detector; the measurement of momentum and time of all the particles in the beam by the Gigatracker (the GTK detector was not available in 2015); a magnetic spectrometer comprising four chambers with STRAW tubes operating in vacuum; a hermetic system of photon veto detectors (LAV, LKr, IRC, SAC); a RICH detector and a muon veto system (MUV) for the particle identification. A detailed description of the NA62 beam line and the detector can be found in [8].

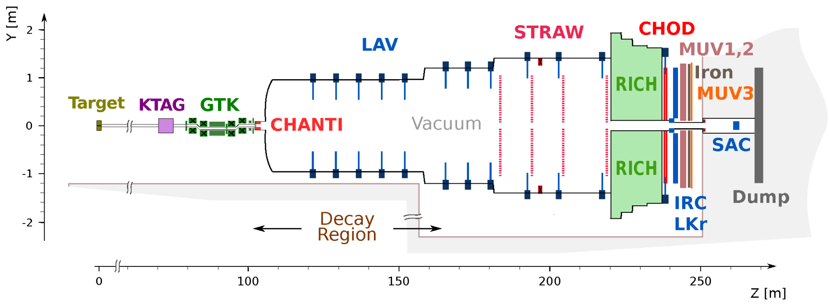


Figure 1: Layout of the NA62 experiment.

The data sample used for the HNL analysis presented in this proceedings was recorded in 5 days of operation during the NA62 pilot run in 2015 at beam intensity varying from 0.4% to 1.3% of the nominal value with a minimum bias trigger scheme. The low-level trigger chain used in the present analysis required a CHOD signal in anti-coincidence with a MUV3 signal; the trigger was not scaled down. The high-level software trigger required a multiplicity requirement in the KTAG detector compatible with a K^+ signal.

1.3 Event Selection and Data Samples

With the assumption of $|U_{\ell 4}|^2 < 10^{-4}$ and considering HNL decays into SM particles, the mean free path of HNLs produced in NA62 for any mass in the considered range (above 170 MeV/c^2) is greater than 10 km and therefore their decays in-flight can be neglected.

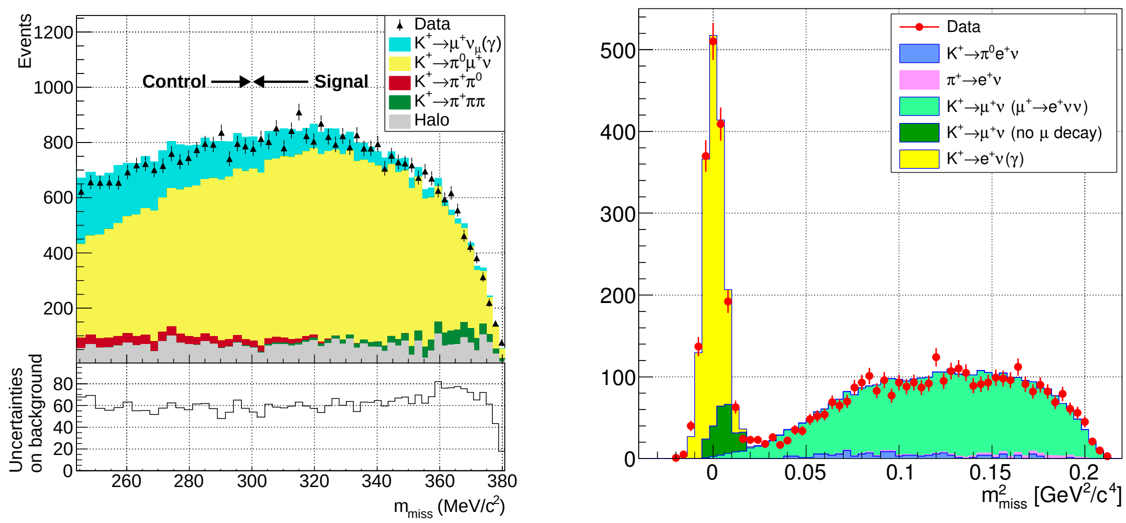
The event selection for both presented analyses requires a single positively charged track reconstructed in the spectrometer within the acceptances of the downstream detectors which are used for the particle identification. The kaon decay vertex is reconstructed as the point of the closest approach of the track and the beam axis, as monitored with fully reconstructed $K^+ \to \pi^+\pi^-\pi^+$ decays.

In the 2007 data analysis, muons are positively identified by MUV signals associated in time and space with the track; events with EM clusters reconstructed in the LKr, not associated to the muon track, are rejected.

In the 2015 data analysis, electrons are identified by the ratio of energy deposit in the LKr to momentum measured by the spectrometer and by an identification algorithm based on the RICH hit pattern. Various background contributions are suppressed by rejecting events with an activity in the LAV, SAC, IRC and CHANTI detectors, and by requesting the presence of a kaon signal in the KTAG matched in time with the track time.

The squared missing mass is computed as $m^2_{\text{miss}} = (P_K - P_\ell)^2$, where P_K and P_ℓ are the kaon and lepton 4-momenta, respectively. The kaon 4-momentum is evaluated from the average 3-momentum (monitored with $K^+ \to \pi^+\pi^-\pi^+$ decays) in the K^+ mass hypothesis, while P_ℓ is the 4-momentum is obtained from the reconstructed 3-momentum of the track in the corresponding ℓ^+ mass hypothesis.

The spectra of missing mass (squared) of the selected $K_{\mu 2}$ (K_{e2}) event candidates from both data and simulation are presented in Fig. 2. The total number of kaon decays in the fiducial regions, N^ℓ_K, is computed from the numbers of selected data events with m^2_{miss} in the SM region and by the acceptance evaluated using the MC simulation. The obtained numbers of kaon decays are $N^\mu_K = (5.977 \pm 0.015) \times 10^7$ (2007 data analysis) and $N^e_K = (3.01 \pm 0.011) \times 10^8$ (2015 data analysis).



(a) $K_{\mu 2}$ candidates, 2007 data sample.

(b) K_{e2} candidates, 2015 data sample.

Figure 2: (a) Missing mass distribution of $K_{\mu 2}$ candidates and background estimate in the signal and control regions. Error bars are data statistical errors. The lower plot shows the total uncertainty on the background estimate. (b) Spectrum of missing mass squared of the selected K_{e2} candidates.

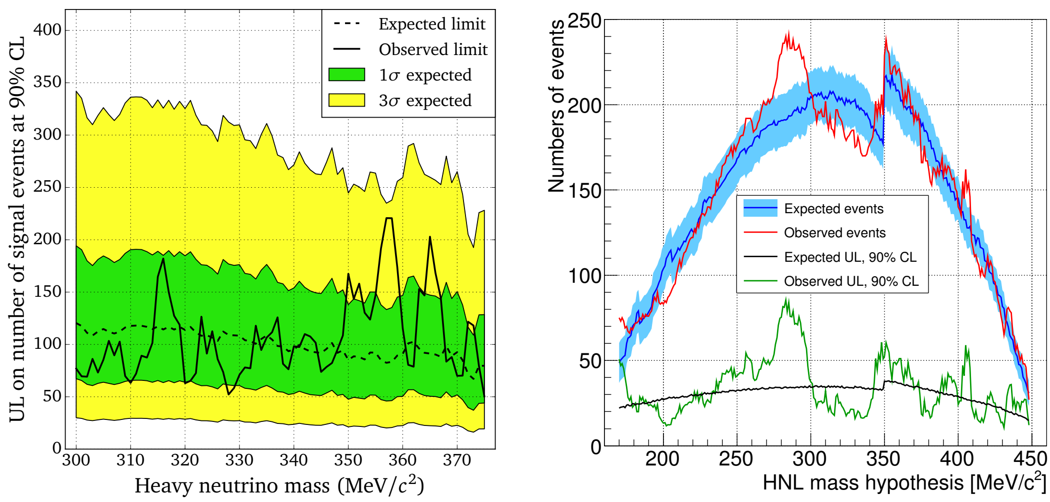
1.4 Search for Heavy Neutrino Production

Both analyses look for the production of HNLs by searching for peaks in the missing mass spectra. The HNL signal regions are defined as $300 < m_{\text{miss}} < 375\,\text{MeV}/c^2$ for the 2007 data analysis and $170 < m_{\text{miss}} < 448\,\text{MeV}/c^2$ for the 2015 data analysis. The peak search is performed in the signal regions with a step of $1\,\text{Mev}/c^2$ with the additional condition on the reconstructed missing mass to be within the $\pm\sigma_h^\ell$ window of the assumed HNL mass, where σ_h depends on the HNL mass resolution evaluated with MC simulations. The statistical analysis is performed by applying the Rolke–Lopez method [9] to find the 90% confidence intervals for the number of reconstructed $K^+ \to \ell^+ N$ decays. Inputs to the computation in each mass window are the number of data events observed, and the estimate of the total number of background events with its uncertainty.

In the 2007 data analysis the number of background events receives contributions from muon halo, evaluated with a control data sample, and from kaon decays, evaluated with simulation. In the 2015 data analysis the background in each mass hypothesis is evaluated from side bands of the data m_{miss} distribution.

2. Upper Limits on the Heavy Neutrino Production

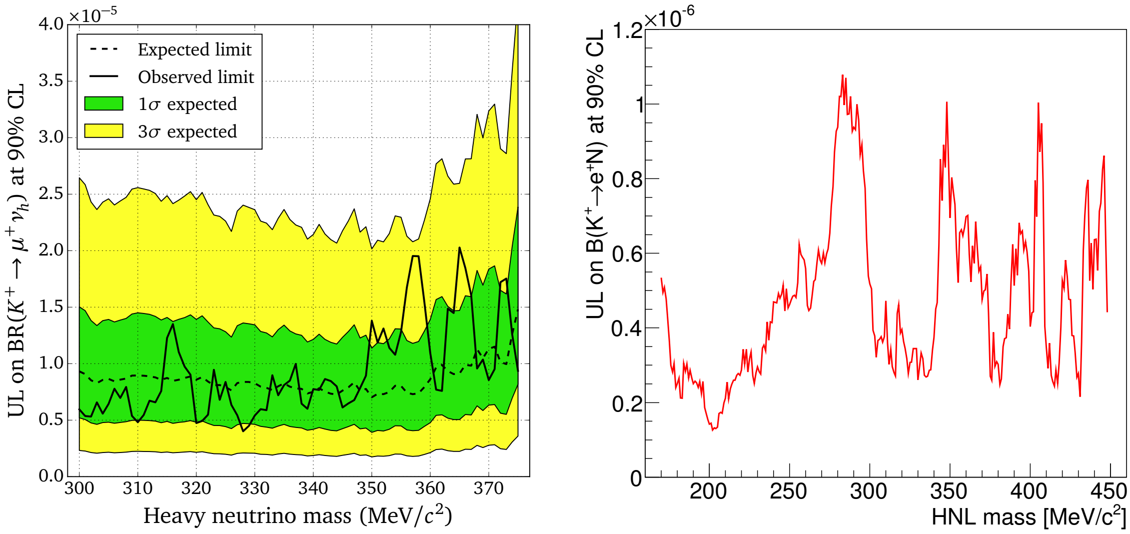
Since no statistically significant HNL production signal is observed, upper limits (ULs) on the number of signal events are established, the expected and observed limits at 90% CL are shown in Fig. 3. A loose selection with a relaxed vertex longitudinal position cut is applied for the K_{e2} data analysis for mass hypotheses of $350\,\text{MeV}/c^2$ and higher, resulting in the discontinuity of the selection acceptance.



(a) $K_{\mu 2}$ analysis, 2007 data sample. (b) K_{e2} analysis, 2015 data sample.

Figure 3: Expected and observed upper limits on the number of signal events at 90% CL for each HNL mass hypothesis. Figure (b) also includes numbers of observed events and expected background events with their uncertainties (shaded blue region).

The upper limits on the number of observed signal events in Fig. 3 are converted into upper limits on the branching fraction $\mathscr{B}(K^+ \to \ell^+ N)$ for each HNL mass hypothesis (see Fig. 4) using the relation between the expected number of signal events N_S^ℓ, the signal selection acceptance A_ℓ^N and the branching fraction: $N_S^\ell = N_K^\ell \cdot \mathscr{B}(K^+ \to \ell^+ N) \cdot A_\ell^N$.



(a) $K_{\mu 2}$ analysis, 2007 data sample. (b) K_{e2} analysis, 2015 data sample.

Figure 4: Expected and observed upper limits on $\mathscr{B}(K^+ \to \ell^+ N)$ at 90% CL for each HNL mass hypothesis.

The upper limits on the mixing parameter $|U_{\ell 4}|^2$ for each HNL mass hypotheses are computed using the limits on the branching fraction and the equation (1). Figure 5 shows the obtained ULs at 90% CL together with the limits from previous HNL production searches in π^+ [10, 11] and K^+ [12, 13] decays. The new NA62 results presented in this proceedings improve the existing limits both on $|U_{\mu 4}|^2$ and $|U_{e4}|^2$ in the analyzed signal regions.

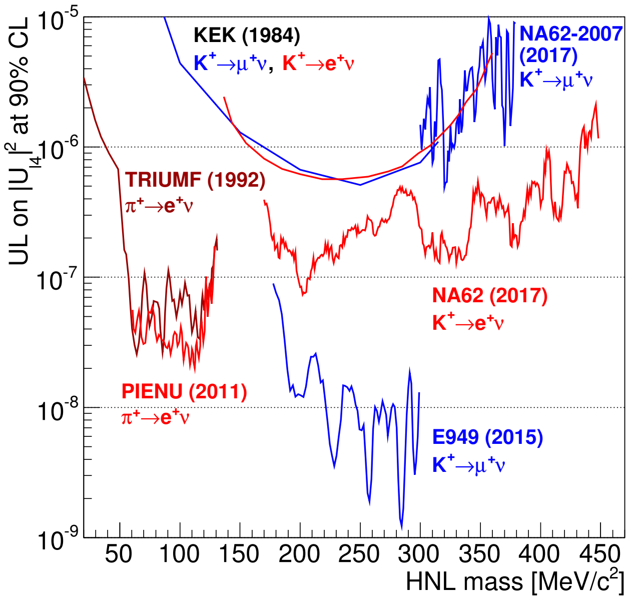


Figure 5: Upper limits on $|U_{\ell 4}|^2$ at 90% CL from the presented NA62 analyses compared to the limits established by earlier HNL production searches in π^+ and K^+.

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