EPJ Web of Conferences **179**, 01009 (2018) https://doi.org/10.1051/epjconf/201817901009
FCCP2017

NA62 and NA48/2 results on search for Heavy Neutral Leptons

Gianluca Lamanna[1,a] for the NA62 collaboration[,b]

[1] *INFN & Physics Department, University of Pisa, Largo Pontecorvo,3 - 50131, Pisa*

Abstract. In this paper we present new results on upper limits for the search of Heavy Neutral Leptons (HNL) with data collected by NA48/2 (2003-2004), NA62-RK (2007) and NA62 (2015) CERN experiments. The data collected with different trigger configuration allow to search for both long and short living heavy neutrinos in the mass range below the kaon mass. In addition the status of the search for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ with the NA62 detector will be briefly presented.

1 Introduction

Although neutrinos in Standard Model (SM) are mass-less, the experimental observation of neutrinos oscillations is a clear indication that neutrinos are massive. Several extensions of SM try to accommodate this experimental evidence by introducing new degrees of freedom, as, for instance, the possibility to have right-handed sterile neutrinos.

One of the simplest model to extend the SM in this sector is the Neutrino Minimal Standard Model (νMSM) [1]. In this model 18 new parameters are introduced in the Lagrangian to explain simultaneously neutrinos oscillation, dark matter and baryon asymmetry in the Universe. The new Lagrangian generates three new massive right-handed neutrinos. The lightest, with mass O(1 keV) is considered as a possible dark matter candidate, while the others, with mass ranging from hundreds of MeV to few GeV, give masses to the SM neutrinos through the see-saw mechanism and introduce next phases in SM, with respect to the CKM phases, becoming a new source of CP violation. The masses of these Heavy Neutral Leptons (HNL) are chosen to be below the electroweak scale and, in principle, can be produced in meson decays. The search in the kaon sector is one of the most promising for large part of the parameter phase space.

The NA48/2 and NA62 experiments, located at the Super Proton Synchrotron (SPS) at CERN, collected, starting from 2003, large samples of kaon decays. This report presents three different and complementary high statistics searches, performed in three different experimental setup with charged kaons decaying in flight.

2 The NA48/2 and NA62 experiments at CERN.

The primary goal of the NA48/2 experiment was to search for CP violation in charged kaon sector through the study of the Dalitz Plot in the three pions decay [2]. The detector based on the NA48 setup, a part some minor changes, is discussed in details in [3]. The experiment used 400 GeV/c protons extracted from the SPS accelerator, impinging on a beryllium target to produce a secondary hadron beam. A system of magnets and collimators selects charged beams with central momentum of 60 GeV (± 3 *GeV*). Both negative and positive charged particles are transported to a 114 m long fiducial decay region in

[a]e-mail: gianluca.lamanna@cern.ch

[b]R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, M. Barbanera, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blazek, B. Bloch-Devaux, V. Bonaiuto, M. Boretto, M. Bragadireanu, D. Britton, F. Brizioli, M.B. Brunetti, D. Bryman, F. Bucci, T. Capussela, A. Ceccucci, P. Cenci, V. Cerny, C. Cerri, B. Checcucci, A. Conovaloff, P. Cooper, E. Cortina Gil, M. Corvino, F. Costantini, A. Cotta Ramusino, D. Coward, G. D'Agostini, J. Dainton, P. Dalpiaz, H. Danielsson, N. De Simone, D. Di Filippo, L. Di Lella, N. Doble, B. Dobrich, F. Duval, V. Duk, J. Engelfried, T. Enik, N. Estrada-Tristan, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, A. Filippi, M. Fiorini, J. Fry, J. Fu, A. Fucci, L. Fulton, E. Gamberini, L. Gatignon, G. Georgiev, S. Ghinescu, A. Gianoli, M. Giorgi, S. Giudici, F. Gonnella, E. Goudzovski, C. Graham, R. Guida, E. Gushchin, F. Hahn, H. Heath, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, B. Jenninger, K. Kampf, V. Kekelidze, S. Kholodenko, G. Khoriauli, A. Khotyantsev, A. Kleimenova, A. Korotkova, M. Koval, V. Kozhuharov, Z. Kucerova, Y. Kudenko, J. Kunze, V. Kurochka, V.Kurshetsov, G. Lanfranchi, G. Lamanna, G. Latino, P. Laycock, C. Lazzeroni, M. Lenti, G. Lehmann Miotto, E. Leonardi, P. Lichard, L. Litov, R. Lollini, D. Lomidze, A. Lonardo, P. Lubrano, M. Lupi, N. Lurkin, D. Madigozhin, I. Mannelli, G. Mannocchi, A. Mapelli, F. Marchetto, R. Marchevski, S. Martellotti, P. Massarotti, K. Massri, E. Maurice, M. Medvedeva, A. Mefodev, E. Menichetti, E. Migliore, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, M. Napolitano, I. Neri, F. Newson, A. Norton, M. Noy, T. Numao, V. Obraztsov, A. Ostankov, S. Padolski, R. Page, V. Palladino, C. Parkinson, E. Pedreschi, M. Pepe, M. Perrin-Terrin, L. Peruzzo, P. Petrov, F. Petrucci, R. Piandani, M. Piccini, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, M. Raggi, A. Romano, P. Rubin, G. Ruggiero, V. Ryjov, A. Salamon, C. Santoni, G. Saracino, F. Sargeni, V. Semenov, A. Sergi, A. Shaikhiev, S. Shkarovskiy, D. Soldi, V. Sougonyaev, M. Sozzi, T. Spadaro, F. Spinella, A. Sturgess, J. Swallow, S. Trilov, P. Valente, B. Velghe, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, H. Wahl, R. Wanke, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko.

vacuum, where K^+ and K^- decays are registered simultaneously with the same detectors.

A spectrometer, housed in a helium vessel located just after the vacuum tank, thanks to a thin Kevlar window, is composed by four drift chambers (DCH) and a dipole magnet. The Spectrometer allows to measure the charged kaon decay products momentum with a resolution of $\sigma_p/p = (1.02 \oplus 0.044\ p)\%$ where p is in GeV/c. The photon detection is performed by a quasi-homogeneous liquid Krypton calorimeter (LKr), with a depth of 27 X_0. The LKr has a resolution of $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ with E in GeV. Other detectors, for particle identification and trigger purpose, complete the setup. The data taking took place in 2003-2004 collecting a total of about 3×10^9 $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$, about 9×10^7 $K^\pm \to \pi^\pm\pi^0\pi^0$ and other decays for rare processes studies.

The data taking in 2007 was devoted to the measurement of the R_K ratio [4]. The NA62-RK collaboration used a slightly modified beam line and detector with respect to the NA48/2 experiment, to collect at lower intensity (by a factor of 10) kaon decays in two leptons. The nominal beam momentum was 74 GeV and the trigger was designed to maximize the number of decays in electron and neutrino collected.

The NA62 collaboration developed a completely new apparatus with respect to the previous experiments. The main goal is to measure the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$ with 10% precision. The first physics run started in 2016, after a period of detectors commissioning. The proton beam extracted from the SPS is used to generate a secondary hadron beam selected in charge (positive) and momentum (75 GeV/c) through a system of dipoles and collimators. The nominal intensity is of 750 MHz, but only a small fraction of the hadrons in the beam are kaons (about $\sim 6\%$). The kaons are positively identified by a Cherenkov beam detector (KTAG). The momentum of each particle in the beam is measured by a beam spectrometer composed by three stations of silicon pixels detector (Gigatracker) exposed at full intensity. An about 150 m long decay region is followed by a straw tubes spectrometer in vacuum in order to minimize the material present along the path of the photons produced in kaon decays (mainly $K^+ \to \pi^+\pi^0$). These photons are detected by the LKr calorimeter and a system of vetoes placed along the fiducial volume (12 rings of lead glass) and around the beam direction. The photon veto system guarantees a coverage up to 50 mrad. The particle identification is done by using a Ring Imaging Cherenkov (RICH), electromagnetic and hadronic calorimeters, and Muon Veto (MUV). A detailed description of the NA62 beam line and detectors can be found in [5].

3 Strategies for Heavy Neutrino searches

Two different strategies can be used to look for HNL in kaons. The first approach directly searches for decay of HNL in a pair of opposite charge particle, depending on the assumption made on the new particle properties. The second approach searches for HNL produced in kaon and pion decays by looking for peaks in the missing mass spectrum in two body decay.

The huge sample of three tracks events collected by the NA48/2 experiments allows to use the first approach to search for HNL decay. On the other hand the search in production is performed in the NA62-RK and NA62 experiments where the single charged particle missing mass is used to look for rare processes.

3.1 NA48/2: HNL search in $K^\pm \to \pi\mu\mu$

Short-living sterile neutrinos decaying promptly to $\pi\mu$ have been searched in the data sample $K^\pm \to \pi\mu\mu$ by NA48/2 in data collected in 2003-2004. The heavy neutrino is produced in $K^\pm \to \mu^\pm N_4$ decay where $N_4 \to \pi^\pm\mu^\mp$. Since the new state decays in the same primary vertex, the $\pi\mu$ pair would produce a narrow peak in the $M_{\pi\mu}$ spectrum (the invariant mass distribution). In the νMSM framework the branching ratio of this decay is proportional to mass and mixing mass matrix element introduced by the new particle:

$$BR(N_4 \to \pi\mu) \sim |U_{l4}| \cdot m_N^3$$

Two different samples were collected by NA48/2: lepton number violating decays $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ ($K^{LNV}_{\pi\mu\mu}$) where the muons have the same sing and lepton number conserving candidates $K^\pm \to \pi^\pm\mu^\pm\mu^\mp$ ($K^{LNC}_{\pi\mu\mu}$) where the muons have opposite sign. Since the lifetime of the possible new particle is supposed to be shorter than $\sim 10\ ps$, the topology of the event, K^{LNV} and K^{LNC}, is indistinguishable from a three track event, both at trigger and preliminary offline selection stage. The frequent $K^\pm \to \pi^\pm\pi^+\pi^-$ ($K_{3\pi}$) decay is used as normalization channel in order to evaluate the number of kaons decaying in the 98 m fiducial region. The similar geometrical acceptance and trigger efficiency between signal and normalization allow a first order cancellation of systematic effects. For each track a momentum between 5 and 55 GeV/c is required, while the total longitudinal momentum must be compatible with the beam momentum and the total transverse momentum must be less than 10 MeV/c. The pion and muon identification is done by using the MUV detector and the energy deposited in the LKr with respect to the momentum as measured by the DCH. For each event with vertex in the decay region the invariant mass $M_{\pi\mu\mu}$ is computed.

The signal region is defined with $|M_{\pi^\mp\mu^\pm\mu^\pm} - M_K| < 5\ MeV/c$ and $|M_{\pi^\pm\mu^\pm\mu^\mp} - M_K| < 8\ MeV/c$ (M_K is the nominal kaon mass) for LNV and LNC respectively. The different cuts are due to different background contamination. In Fig. 1 the invariant mass of all events passing the selection are shown, for both data and Monte Carlo. For the LNV selection one event is observed in the signal region with a background expectation of $N_{bkg} = 1.16 \pm 0.87_{stat} \pm 0.12_{syst}$, evaluated with Monte Carlo simulation, due to $K_{3\pi}$ with two pions decaying in muons. An upper limit (90 % confidence level) is set to $BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm)$ with the Rolke-Lopez method [6]:

$$BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 8.6 \times 10^{-11}$$

 https://doi.org/10.1051/epjconf/201817901009

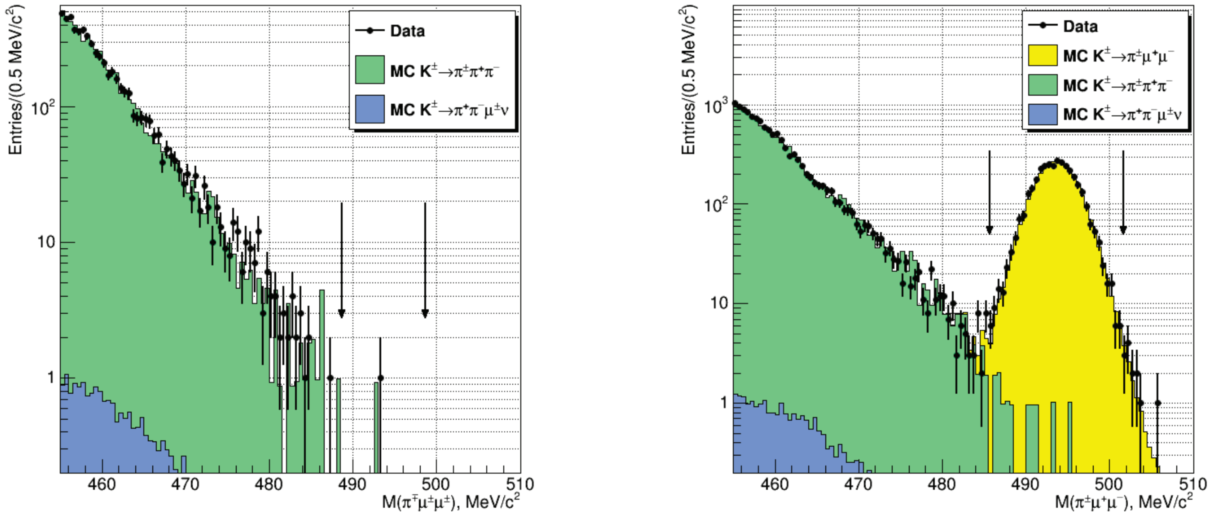

Figure 1. Invariant $M_{\pi\mu\mu}$ mass distribution for SM forbidden LNV (left) and SM allowed LNC (right) decays.

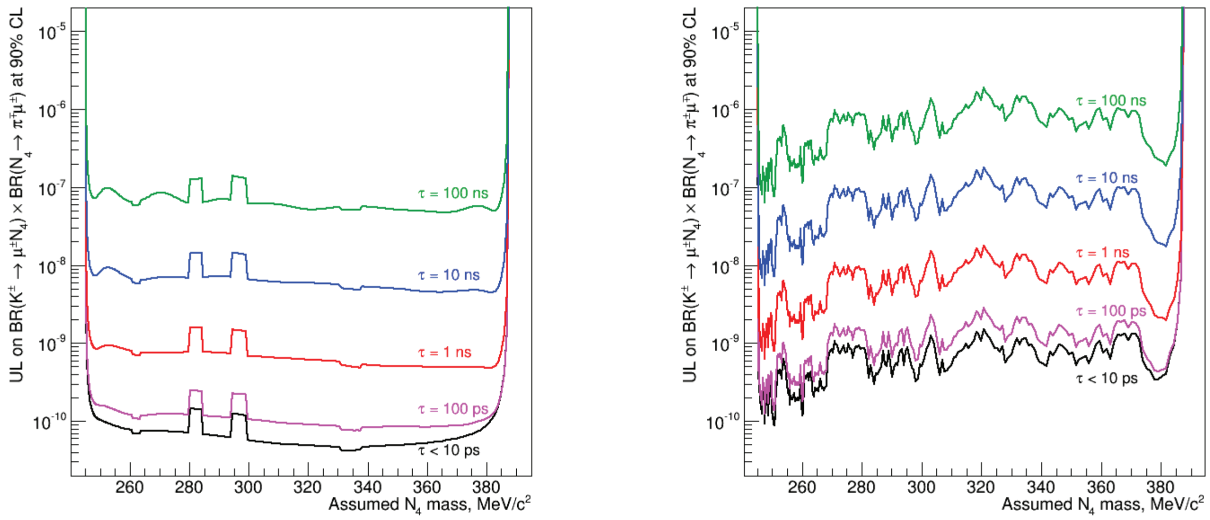

Figure 2. Upper limits at 90% CL for the $BR(K^\pm \to \mu^\pm N_4)BR(N_4 \to \pi^\mp\mu^\pm)$ (left) and $BR(K^\pm \to \mu^\pm N_4)BR(N_4 \to \pi^\pm\mu^\mp)$ (right).

For all the events survived to the selection, both for LNV and LNC, a scan of the invariant $M_{\pi\mu}$ mass is performed in order to search for two-body resonances. The mass steps are given by $\sigma(M_{\pi\mu})/2$, where $\sigma(M_{\pi\mu})$ is the mass resolution. In total 284 and 267 bins are considered for LNV and LNC respectively. In each mass bin the significance of the signals never exceed 3 standard deviations. The Upper Limits on the product $BR(K^\pm \to \mu^\pm N_4)BR(N_4 \to \pi^\mp\mu^\pm)$ and $BR(K^\pm \to \mu^\pm N_4)BR(N_4 \to \pi^\pm\mu^\mp)$ are evaluated as a function of the mass hypothesis (M_i) and the lifetime of the possible resonance (τ), by using the Rolke-Lopez method. The results are shown in Fig. 2.

The upper limit on $BR(K^\pm \to \mu^\pm N_4)BR(N_4 \to \pi\mu)$ can be used to define the upper limit on the matrix element $|U_{\mu 4}|$ according to [7].

3.2 NA62-RK and NA62: HNL search in $K^+ \to l^+\nu$ ($l = \mu, e$)

NA62-RK collected data in 2007, with a trigger optimized to collect leptonic kaon decays, with electrons and muons. This allows to search for $K^+ \to \mu^+ N_4$. Assuming heavy neutrinos decaying only in standard model particles with a lifetime $\tau > 1\mu s$ (which corresponds to $|U_{\mu 4}|^2 < 10^{-4}$), the mean free path in the mass range considered is longer than 10 Km. For this reason the only expected signature is a narrow peak in the muon missing mass. The events are selected by requiring a single track identified as a muon, coming from the decay region and with momentum compatible with a kaon decay. The missing mass is defined as $m^2_{miss} = (P_K - P_{track})^2$ where P_{track} represents the 4-momentum as reconstructed by the spectrometer and P_K the nominal kaon 4-momentum evaluated as the average of the 3π total momentum in the $K^+ \to \pi^+\pi^+\pi^-$ decay. The signal region is defined as $300 < m_{miss} < 375 (MeV/c^2)$. A total of $N_{\mu\nu} = 5.977 \times 10^7$ events are selected in the data

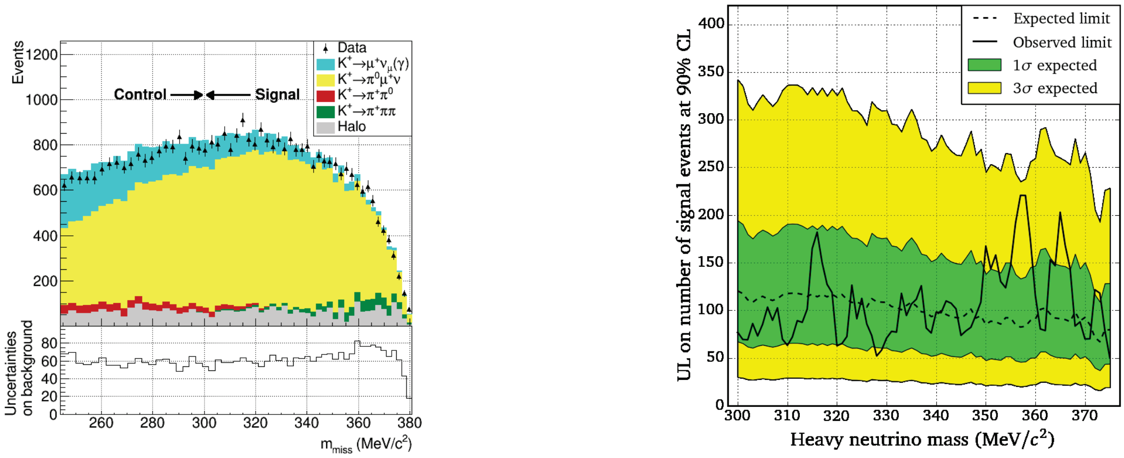

Figure 3. Reconstructed missing mass in $K \to \mu^+ N_4$ hypothesis (2007 data) (left); Upper limit on number of signal events in $K \to \mu^+ N_4$ hypothesis (2007 data) (right).

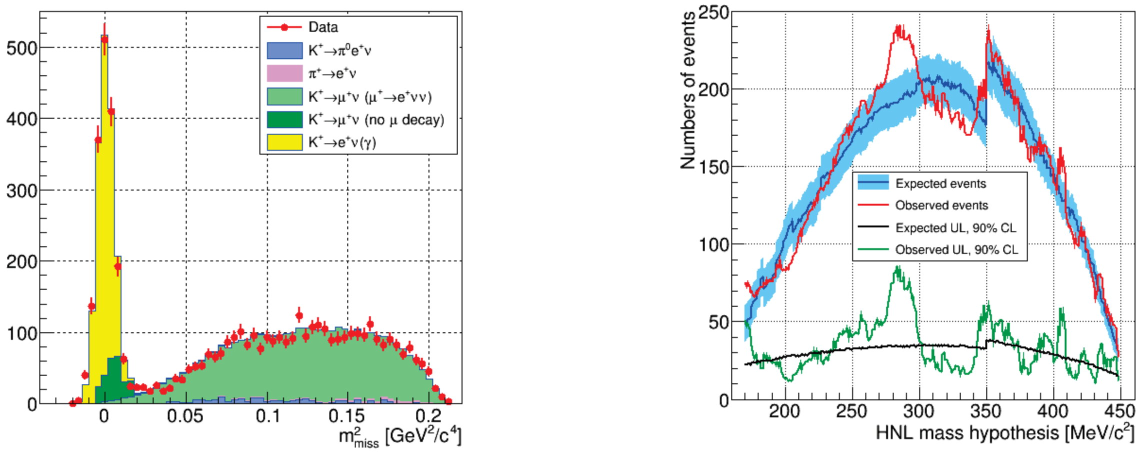

Figure 4. Reconstructed missing mass in $K \to e^+ N_4$ hypothesis (2015 data) (left); Upper limit on number of signal events in $K \to e^+ N_4$ hypothesis (2015 data) (right).

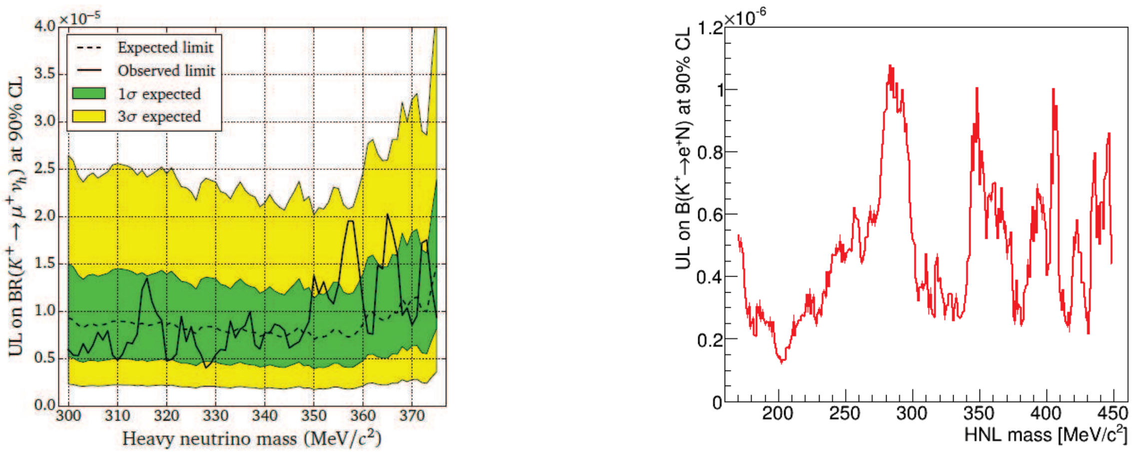

Figure 5. Upper limit on BR($K^+ \to \mu^+ N_4$) (2007 data) (left); Upper limit on BR($K^+ \to e^+ N_4$) (2015 data) (right).

sample considered for this analysis. Possible contribution to the background from other kaon decays is evaluated by Monte Carlo, while the main background from the beam halo muon components is studied using a control sample, obtained with the K^- beam only. In Fig. 3 (left) the missing mass spectrum is shown together with the background contribution.

The peak search is performed in steps of 1 MeV/c^2 in the signal region. For each bin of missing mass the Rolke-Lopez method for the case of a Poisson process in presence of gaussian background is applied to find the 90% confidence intervals. No significance above three sigma is found in the whole region considered (Fig. 3 (right)). The upper limit on the number of observed events ($N_{\mu N}$) is converted in an upper limit on the BR($K^+ \to \mu^+ N_4$) using the number of kaon decays (N_K) and the acceptance given by the Monte Carlo ($A_{\mu N}$) for each mass hypothesis:

$$BR(K^{\pm} \to \mu^+ N_4) = \frac{N_{\mu N}}{N_K \cdot A_{\mu N}}$$

In Fig. 5 (left) the limits on the BR is shown. These limits can be used to constrain the $|U_{l4}|^2$ matrix element by using the following formula:

$$|U_{\mu 4}|^2 = \frac{BR(K^+ \to \mu^+ N_4)}{BR(K^+ \to \mu^+ \nu) \cdot \rho(M_{N_4})}$$

where $\rho(M_{N_4})$ is a kinematical factor to account for the heavy neutrino mass. Similar search in the $K^+ \to e^+ N_4$ channel, is performed on the 2015 data collected by the completely new NA62 apparatus during 5 days of special minimum bias run. In Fig. 4 (left) the missing mass is shown. A total of $N_{ev} = 3.01 \times 10^8$ events are selected with background coming from kaon and pion decays. The mass scan, in step of 1 MeV/c^2, is performed in the signal region of $170 < m_{miss} < 448(MeV/c^2)$. The upper limit on the expected events is shown in Fig. 4 (right), while the corresponding upper limit on the BR($K^+ \to e^+ N_4$) is shown in Fig. 5 (right).

4 Status of the $K^+ \to \pi^+ \nu \bar{\nu}$ analysis in NA62.

NA62 collected data for $\pi \nu \bar{\nu}$ analysis in 2016 with reduced intensity (40%) with respect to the nominal intensity of 3×10^{12} pps. About 5% of these data, corresponding to 2.3×10^{10} kaons, have been preliminary analyzed in order to study signal sensitivity and background.

A reduction factor of $O(10^{12})$ on background rejection must be obtained exploiting both kinematical differences between signal and other most frequent kaon decays and active vetoes by detectors designed on purpose. The pion missing mass, the main kinematic variable used for signal to background separation, is defined as $m^2_{miss} = (P_K - P_\pi)^2$, where P_K is the kaon 4-momentum as measured by the GTK and P_π is the pion momentum as measured by the STRAWS spectrometer. This variable allows to define two regions with reduced background contribution. The remaining background contamination in the two regions,

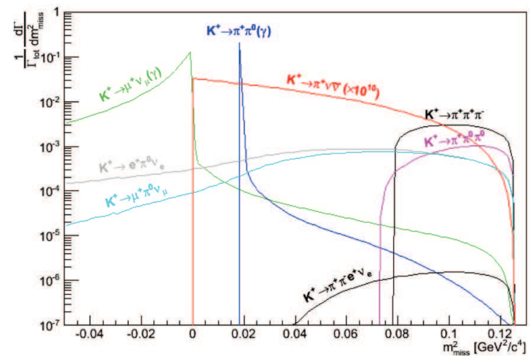

Figure 6. Missing mass distribution for signal and background. The signal is multiply by a factor 10.

shown in Fig. 6, is due to non Gaussian tails in $K_{2\pi}$ ($K^+ \to \pi^+ \pi^0$) and $K_{\mu 2}$ ($K^+ \to \mu^+ \nu$) decays, kaon decays with neutrinos and undetected or mis-identified particles and beam related background. The signal selection is done by requiring a good single downstream track resolution with no extra in-time activity in the veto detectors (LKr, LAV, IRC, SAC and MUV3) and a good measurement, by the GTK, of the momentum of the kaon identified by the KTAG. The pion identification is done by using RICH and calorimeters (LKr, MUV1 and MUV2) in order to further suppress muons and electrons contribution. The kaon mistagging is at level of 2% for 40% of nominal intensity, while the signal efficiency due to the kaon identification is about 75%. The signal region is limited to 50 m, starting 10 m after the last collimator, in order to suppress the contribution to background from pions originated from beam particles interacting in GTK or from kaons decaying before the fiducial region. In Fig. 7 the selected events are shown in a missing mass versus momentum 2D space. The two red boxes represent the two signal regions.

The level of background in the signal regions, measured from data, is $\sim 6 \times 10^{-4}$ for $K_{2\pi}$ and $\sim 3 \times 10^{-4}$ for $K_{\mu 2}$. The use of the γ-vetoes allows to obtain the level

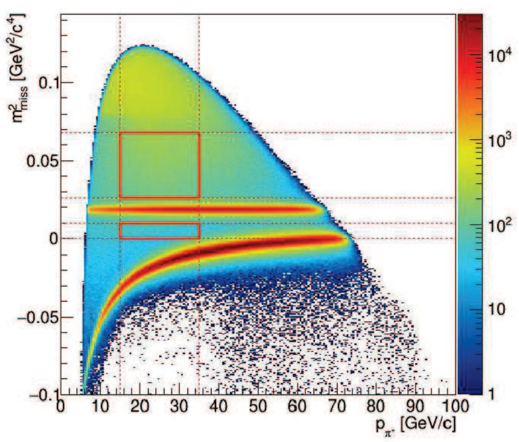

Figure 7. Distribution of m^2_{miss} versus pion momentum in minimum bias sample. The signal regions are identified by red boxes.

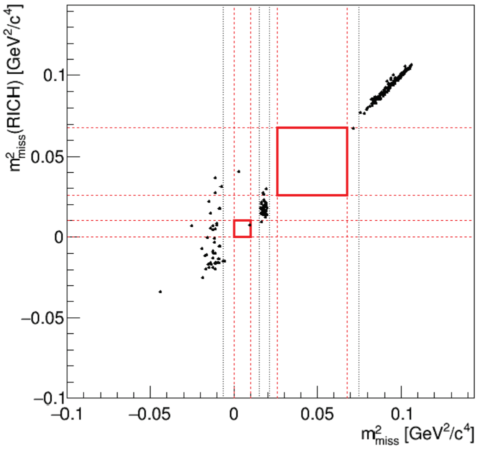

Figure 8. Events passing the full selection (see the text for the axis variable definition). The red lines identify the signal regions, while the black dashed lines the background control regions. The single event present in region 1 is discarded if the missing mass is reconstructed using the nominal beam momentum (to control the GTK non Gaussian tails).

of 1.2×10^{-7} on π^0 reduction, as measured on minimum bias triggered events. The identification of the muon with RICH, MUV3 and calorimeters allows to reach the level of 10^{-7} keeping a $\sim$ 65% of efficiency on positive pion identification.

In Fig. 8 the remaining events are shown: the missing mass is defined both using the pion momentum measured by the STRAWS (X axis) and by the RICH (Y axis) (in pion hypothesis) in order to reduce the contribution of the non Gaussian tails. The kaon flux is measured from a $K^+ \to \pi^+\pi^0$ from a minimum bias trigger. Extrapolating from the control regions, the background in the signal regions is estimated as 0.024, 0.017 and 0.011 events from $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \mu^+\nu$ respectively. The expected number of SM $K^+ \to \pi^+\nu\bar{\nu}$, in the data sample considered, is about 0.064. No events are observed in the signal region.

5 Conclusions

The kaon sector allows to study both short and long-living HNL in the mass range of few hundreds of MeV. NA48/2 sets the world best limit on the BR of a Majorana sterile neutrino from the LNV $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$, improving by an order of magnitude the previous result.

For heavy neutrino lifetime shorter than 100 ps limits in the range $10^{-10} - 10^{-9}$ are set. For stable (or long-living) HNL, the preliminary results in the peak search of HNL by the NA62-RK and the NA62 experiments, both in muon and positron channel, improve the existing limits in $|U_{l4}|$. In Fig. 9 a comparison with the previous HNL searches in π^+ and K^+ is shown. The full analysis of the 2015 minimum bias run is on-going. The background level in the heavy neutrino signal region is a factor 100 lower than in 2007, for both positron and muon channel. This will allow to finally reach a sensitivity of $10^{-6} - 10^{-7}$ on both channels.

The status of the NA62 experiment is presented. A total of 5% of the statistics collected in the 2016 run at 40% of the final beam intensity has been analyzed to study signal acceptance and background. No SM events are expected and observed in the sample considered. The blind analysis of the full 2016 data set is on-going.

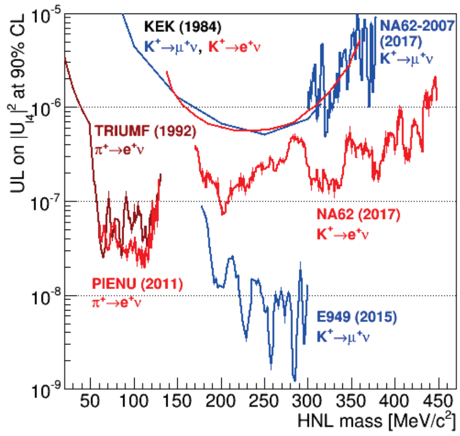

Figure 9. Upper limits on $|U_{l4}|^2$ at 90% CL from NA62 compared to limits coming from previous analysis.

References

[1] T. Asaka and M. Shaposhnikov, Phys. Lett. B **620** (2005) 17 doi:10.1016/j.physletb.2005.06.020 [hep-ph/0505013].

[2] J. R. Batley *et al.* [NA48/2 Collaboration], Eur. Phys. J. C **52** (2007) 875 doi:10.1140/epjc/s10052-007-0456-7 [arXiv:0707.0697 [hep-ex]].

[3] V. Fanti *et al.* [NA48 Collaboration], Nucl. Instrum. Meth. A **574** (2007) 433. doi:10.1016/j.nima.2007.01.178

[4] C. Lazzeroni *et al.* [NA62 Collaboration], Phys. Lett. B **698** (2011) 105 doi:10.1016/j.physletb.2011.02.064 [arXiv:1101.4805 [hep-ex]].

[5] E. Cortina Gil *et al.* [NA62 Collaboration], JINST **12** (2017) no.05, P05025 doi:10.1088/1748-0221/12/05/P05025 [arXiv:1703.08501 [physics.ins-det]].

[6] J. R. Batley *et al.* [NA48/2 Collaboration], Phys. Lett. B **769** (2017) 67 doi:10.1016/j.physletb.2017.03.029 [arXiv:1612.04723 [hep-ex]].

[7] G. Cvetic, C. Dib, S. K. Kang and C. S. Kim, Phys. Rev. D **82** (2010) 053010 doi:10.1103/PhysRevD.82.053010 [arXiv:1005.4282 [hep-ph]].