Search for heavy neutrino in rare kaon decays

A. T. Shaykhiev[a*]

[a] *Institute for Nuclear Research RAS*

60 October Revolution Pr. 7a, 117312 Moscow, Russia

Abstract

According to the νMSM there is a possibility of the heavy neutrino existence with mass in the $\mathcal{O}(1)$ GeV region. The search for rare kaon decays allows to study the heavy neutrino mass interval $M_\pi < m_{\nu_H} < M_K$. In this paper the preliminary E949 (BNL) data analysis is presented, the background sources were studied and there was estimated the sensitivity to $K^+ \to \mu^+\nu_H$ branching ratio. The expected sensitivity to the $BR(K^+ \to \mu^+\nu_H)$ is about 10^{-7}–2×10^{-8} and depends on heavy neutrino mass. It is also possible to exclude the heavy neutrino existence with mass below ~ 160 MeV.

1 Introduction

There are three types of massless neutrino, ν_e, ν_μ, ν_τ, in the Standard Model (SM), but the neutrino oscillations experiments [1, 2, 3, 4, 5, 6] confirm that neutrino has mass and mixing. In the other words, the weak eigenstates ν_e, ν_μ, ν_τ are the linear superposition of the mass eigenstates ν_1, ν_2, ν_3. The SM also cannot explain baryon asymmetry of the Universe and dark matter.

An extension of the SM by three singlet fermions with masses smaller than the electroweak scale without adding any new physical principles (such as supersymmetry or extra dimensions) or new energy scales (like Grand Unified scale) allows to explain simultaneously the phenomena that cannot be fit to the SM. An example of such a theory is the renormalizable extension of the SM, the νMSM (neutrino Minimal Standard Model) [7, 8]. The leptonic sector of this theory has the same structure as the quark sector, i.e. every left-handed fermion has its right-handed counterpart. Though νMSM does not have any extra stable particles in comparison with the SM, the lightest singlet fermion, ν_{H1}, may have a lifetime greatly exceeding the age of the Universe and thus play a role of a dark matter particle. Dark matter sterile neutrino is likely to have a mass in the $\mathcal{O}(10)$ keV region [8, 9]. The interaction strength between ν_{H1} and the matter should be superweak. Two other sterile neutrinos (ν_{H2}, ν_{H3}) should interact with the SM particles more strongly than ν_{H1} to explain the observed pattern of neutrino oscillations. The masses of ν_{H2} and ν_{H3} should lie in the range from $\simeq 150$ MeV to $\simeq 100$ GeV and should be degenerate ($\Delta M_{2,3} \ll M_{2,3}$) to generate baryon asymmetry of the Universe. These two sterile neutrinos are likely to have a masses in the $\mathcal{O}(1)$ GeV [8, 9].

Two strategies can be used for the experimental search of these particles. The first one is related to their production. Since they are massive, the kinematics of, for example, two body decays $K^\pm \to \mu^\pm\nu_\mu$ and $K^\pm \to \mu^\pm\nu_H$ is not the same. So the study of kinematics of rare meson decays can constrain the strength of the coupling of heavy leptons using the following expression [10]:

$$\Gamma(M^+ \to l^+\nu_H) = \rho\Gamma(M^+ \to l^+\nu_l)|U_l|^2,$$

where $M = \pi,\ K$; $l = e,\ \mu$; ρ is kinematical factor and lies in the range from 0 to 4 for $0 < m_{\nu_H} < 300$ MeV. This strategy have been used in a number of experiments for the search

*e-mail: shaykhiev@inr.ru

of neutral leptons in the past [11, 12], where the spectra of electrons and muons originating in decays of pions and kaons have been studied. The second strategy is to look for the decays of heavy leptons to hadrons and leptons (CERN PS191 experiment) [13].

The successful predictions of the Big Bang Nucleosynthesis (BBN) can constrain properties of heavy leptons in the νMSM [9, 14]. The experimental and BBN constrains on heavy neutrino coupling are shown in Fig. 1.

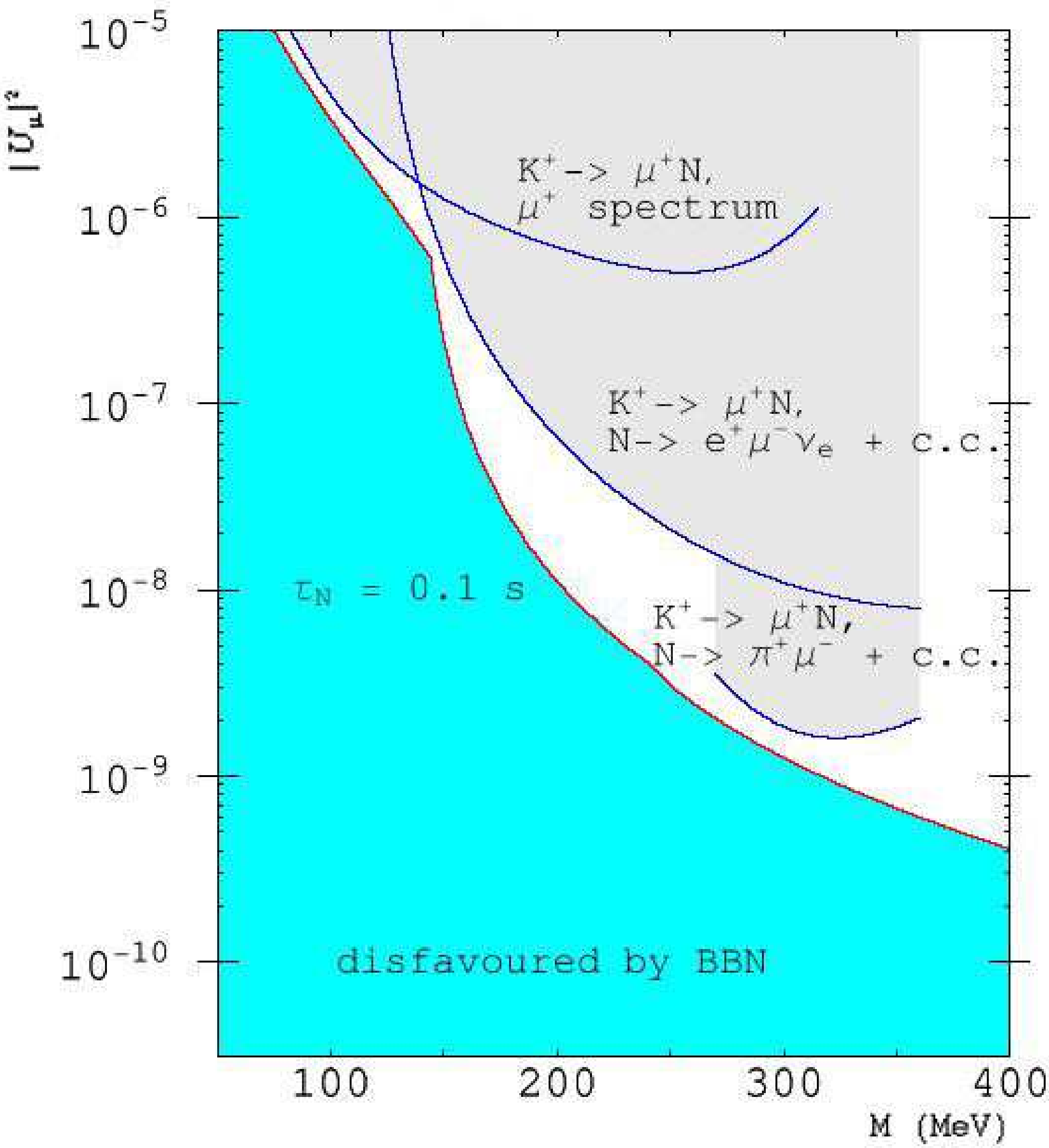

Figure 1: Limits on $|U_\mu|^2$ depending on heavy neutrino mass from BBN (lower bound) and from direct searches in the CERN PS191 experiment and rare kaon decays experiment (upper bounds).

So there is a gap between experimental and BBN constrains for $M_\pi < m_{\nu_H} < M_K$. To study the kinematics of two body decay $K^+ \to \mu^+\nu_H$ it was suggested to use E949 (BNL, USA) experimental data.

2 E949 experiment

The E949 experiment was aimed to measure the branching ratio of rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$, which is a sensitive test of the SM and new physics effects [15]. The E949 result is [16]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}.$$

The E949 detector is shown in Fig. 2. Incoming $\sim$ 710 MeV/c kaons with 3/1 K^+/π^+

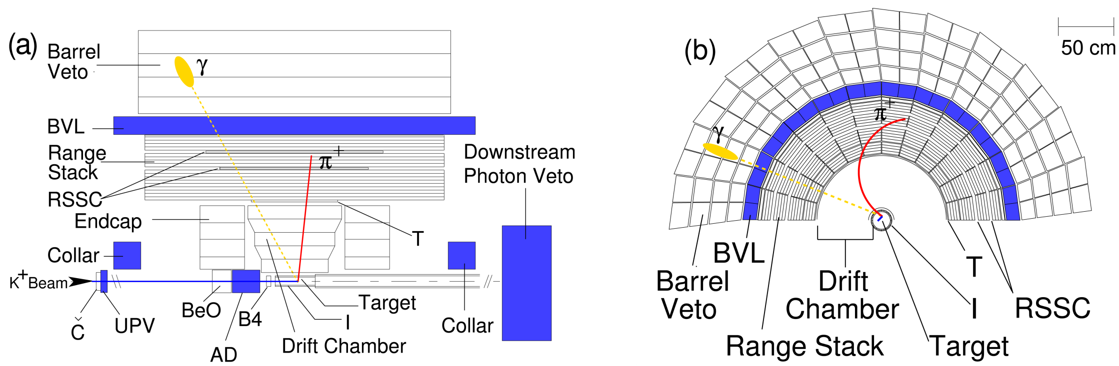

Figure 2: Schematic side (a) and end (b) views of the upper half of the E949 detector. An incoming kaon is shown traversing the beam instrumentation stopping in the target and decaying to $\pi^+\pi^0$. The outgoing charged pion and one photon from $\pi^0 \to \gamma\gamma$ decay are illustrated.

ratio are identified by Čerenkov counter and two proportional wire chambers then slowed down by an inactive degrader and an active degrader, passing through a beam hodoscope, stopping and decaying in the scintillating fiber target. The momentum and trajectory of the outgoing charged particles are measured in a drift chamber (UTC). These particles come to rest in a Range Stack (RS) of 19 layers of plastic scintillator. The primary functions of the RS are energy and range measurements of charged particles and their identification. The innermost counters, called T-counters, serve to define the fiducial volume for kaon decay products.

The detection of any activities coincident with the charged track is very important for suppressing the backgrounds for $K^+ \to \pi^+ \nu\bar{\nu}$ decay. Photons from $K_{\pi 2}$, $K_{\mu\nu\gamma}$, $K_{\mu 3}$ and other radiative decays are detected by hermetic photons detectors (Barrel Veto, BVL, UPV, Collar, Downstream Photon Veto, End Cap) with $\simeq 4\pi$ solid angle coverage as shown in Fig. 2.

The events with a single pion track and no any coincident detector activity are $K^+ \to \pi^+ \nu\bar{\nu}$ candidates.

2.1 The $K^+ \to \mu^+ \nu_H$ trigger

The experimental signature of the $K^+ \to \mu^+ \nu_H$ decay is the same as for the $K^+ \to \pi^+ \nu\bar{\nu}$ decay (one single charged track with no any detector activity). Thats why there was suggested to use the main E949 trigger. This trigger consists of several requirement:

1. Use the stopped kaons. To reject kaon decays-in-flight we used online delay coincidence. It means that outgoing charged particle should leave the target at least 2 ns later than kaon hits the Čerenkov counter.

2. 24 sectors of RS are conventionally grouped into 6; a group of 4 sectors is called a "hextant". Only one hextant is allowed to have charged track or two hextants if they are adjacent. This rejects events with multiple tracks and events with photon activities in RS.

3. A charged track must reach the RS layer 6 or 7. This requirement removes short range tracks from $K^+ \to \pi^+\pi^0\pi^0$, $K^+ \to \pi^+\pi^-\pi^+$ decays.

4. A charged track is not allowed to reach the RS layer 19 to reject μ^+ from $K_{\mu 2}$ decays.

5. Online photon veto in Barrel Veto, BVL and End Cap . Any photon hit which is coincident with charged track and whose energy is above a threshold is not allowed.

6. Online pion identification. This trigger requirement is the worst for heavy neutrino analysis. It requires a signature of $\pi^+ \to \mu^+$ decay in the online stopping counter. The μ^+ from the $\pi^+ \to \mu^+\nu_\mu$ decay at rest has the kinetic energy of 4 MeV (equivalent range in plastic scintillator is 1 mm) and rarely goes out of the stopping counter. So pulses in the stopping counter recorded by the TDs have double-pulse structure up to $\sim$ 70 ns. The single-pulse events were rejected. This requirement decreases E949 trigger efficiency to the $K^+ \to \mu^+\nu_H$ decay in 20–50 times [17].

More detail description of the E949 experiment may be found in [18].

3 Data Analysis

The $K^+ \to \mu^+\nu_H$ is a two-body decay and a corresponding muon momentum can be definitely calculated from:

$$P_\mu = \frac{1}{2} M_K c \sqrt{1 + \left(\frac{m_\mu^2}{M_K^2}\right)^2 + \left(\frac{m_{\nu_H}^2}{M_K^2}\right)^2 - 2\left(\frac{m_\mu^2}{M_K^2} + \frac{m_{\nu_H}^2}{M_K^2} + \frac{m_\mu^2}{M_K^2}\frac{m_{\nu_H}^2}{M_K^2}\right)},$$

where M_K, m_μ, m_{ν_H} are kaon, muon, neutrino masses respectively and P_μ is the muon momentum. To study E949 trigger efficiency (acceptance) to the $K^+ \to \mu^+\nu_H$ decay we used MC simulation. Fig. 3 shows the relation between muon momentum and neutrino mass and the

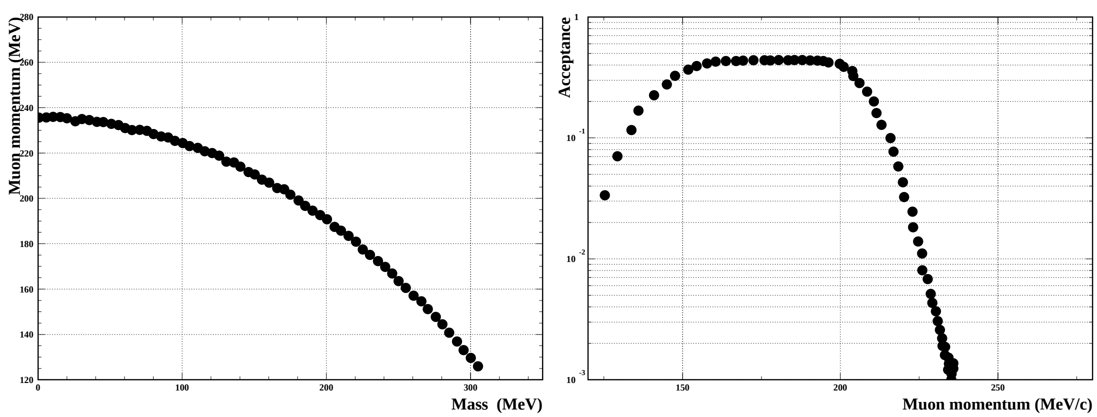

Figure 3: The muon momentum dependence on heavy neutrino mass (left) for the $K^+ \to \mu^+\nu_H$ decay at rest and E949 trigger acceptance dependence on muon momentum (right).

dependence of E949 trigger acceptance on muon momentum. The trigger has maximum acceptance for muon momentum in the 160 MeV/c–205 MeV/c region (equivalent heavy neutrino mass region is from 160 Mev to 260 MeV). It should be remembered that MC simulation does not take into account online pion identification.

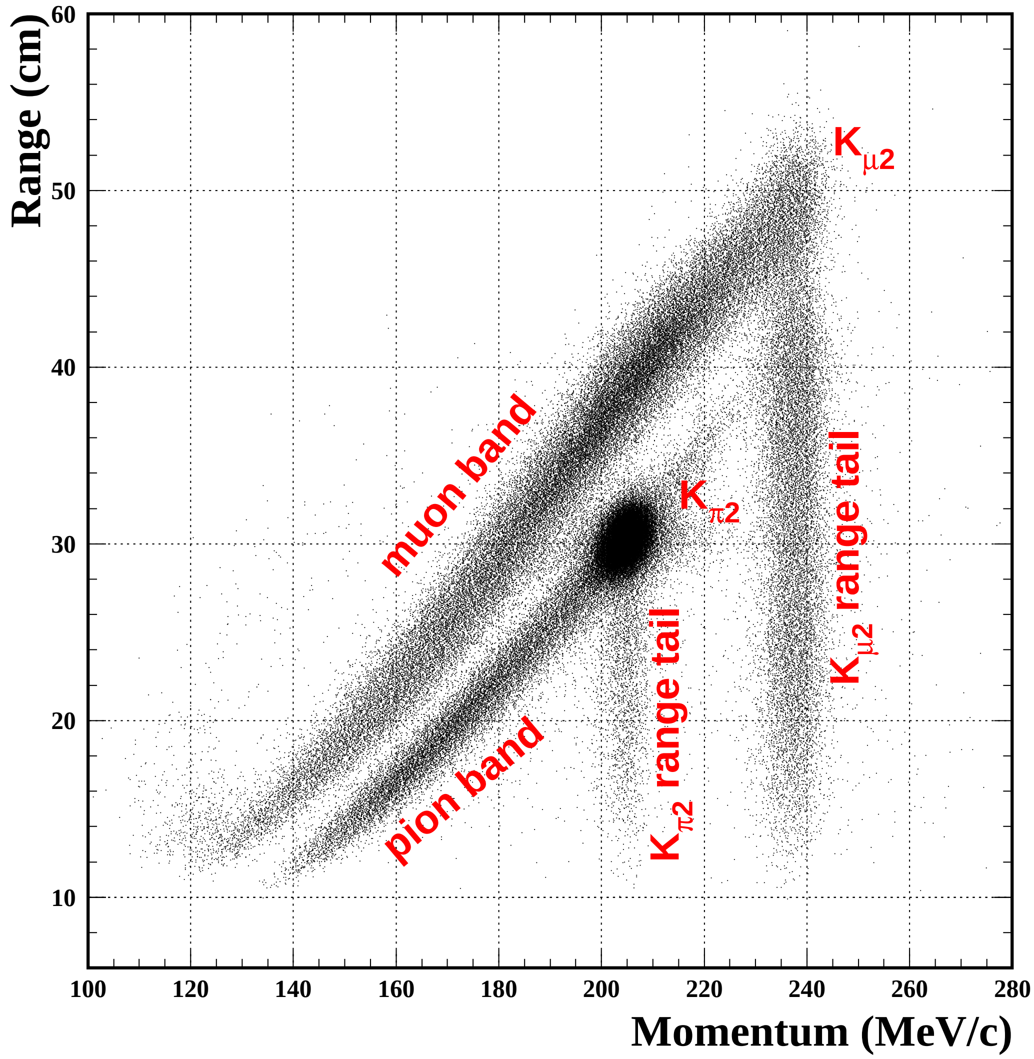

Figure 4: Range in a plastic scintillator and the momentum of the charged particles for events that pass E949 trigger.

3.1 The background study

The search for $K^+ \to \mu^+\nu_H$ is to find additional peak below $K_{\mu2}$ peak. So we should well understand all background sources that can fake or cover our signal. Fig. 4 shows the range in a plastic scintillator and the momentum of the charged particles for events that pass E949 trigger. Events in the muon band are due to multi-body decays, such as $K^+ \to \mu^+\nu_\mu\gamma$ ($K_{\mu\nu\gamma}$), $K^+ \to \mu^+\pi^0\nu_\mu$ ($K_{\mu3}$), π^+ decay in flight and $K^+ \to \mu^+\nu_\mu$ decay with inelastic scattering in the target. Events in the pion band are due to $K^+ \to \pi^+\pi^0\gamma$ decay, pions from the beam that scatter into the Range Stack. Both events in the $K_{\pi2}$ range tail and events in the $K_{\mu2}$ range tail have ranges smaller than that expected from these decays, due to elastic (inelastic) scattering in the Range Stack.

For the particle identification in the detector we used Range-Momentum consistency cut. Muons typically have a longer range than pions when the momentum is the same. The range deviation in the Range Stack is defined as

$$\chi_{R-P} \equiv \frac{R_{meas} - R_{exp}}{\sigma_R},$$

where R_{meas} is the measured range in the RS, R_{exp} is the expected range in the RS, which is calculated from momentum measured by the UTC with an assumption that the track is a pion, and σ_R is the sigma of the measured range as a function of the momentum. The particle was identified as a muon if $\chi_{R-P} \geq 4.2$. It allows to reach pion rejection ~ 500.

The photon veto rejection of the $K^+ \to \mu^+\nu_\mu\gamma$ and $K^+ \to \mu^+\pi^0\nu_\mu$ decays was studied using MC simulation of these decays with gamma energy $E_\gamma > 5$ MeV. Taking into account the branching ratio of the $K_{\mu\nu\gamma}$ (6.2×10^{-3}) and $K_{\mu 3}$ (3.35×10^{-2}) decays, the $K_{\mu 3}$ contribution in the total number of background events is less than 1% of the $K_{\mu\nu\gamma}$ contribution due to two photons in the final state. The $K^+ \to \pi^+\pi^0\gamma$ decay can be ignored due to small branching ratio (2.75×10^{-4}), three photons in the final state and large range-momentum pion rejection. Therefore, the $K^+ \to \mu^+\nu_\mu\gamma$ is the dominant background source for the search of the $K^+ \to \mu^+\nu_H$ decay.

3.2 1/20 of E949 data and comparison with MC simulation

We have $\sim 1.6 \times 10^{12}$ the stopped kaons for our analysis. There was analyzed $\sim 5\%$ of all E949 data. The momentum spectra after applying some offline cuts are shown in Fig. 5. More detail

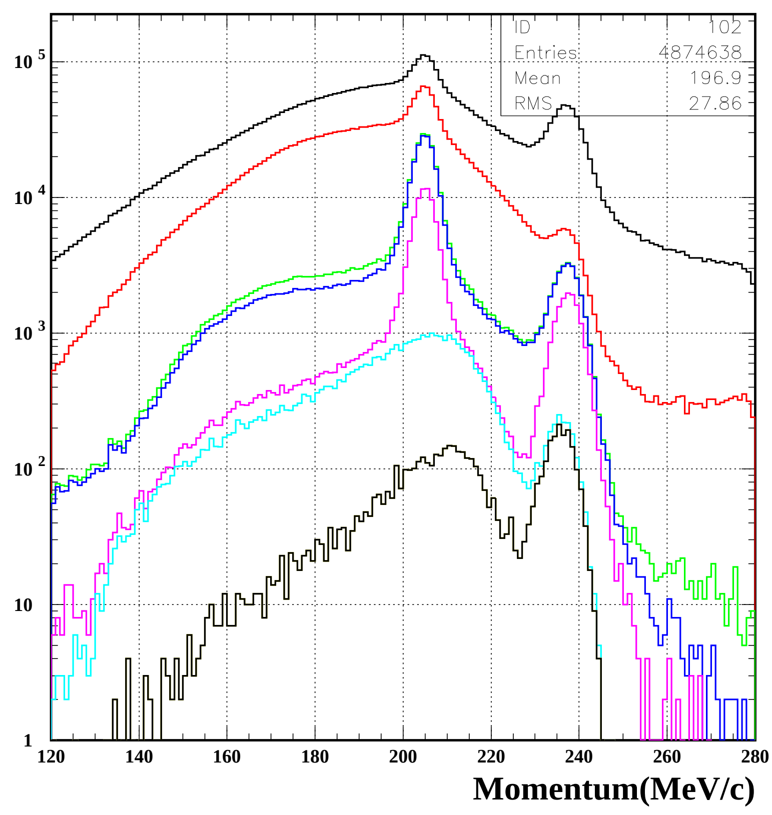

Figure 5: The momentum spectra after applying some groups of cuts. Black line — after E949 trigger, red line — after kinematics cuts, green line — after beam cuts, blue line — after DELCO2, magenta line — after target cuts,light blue line — after Range-Momentum, grey line — after Photon Veto

description of the offline cuts may be found in [18]. To check our suggestion about the dominant background source we simulated the muon momentum spectrum of the $K_{\mu\nu\gamma} + K_{\mu 2}$ decay and

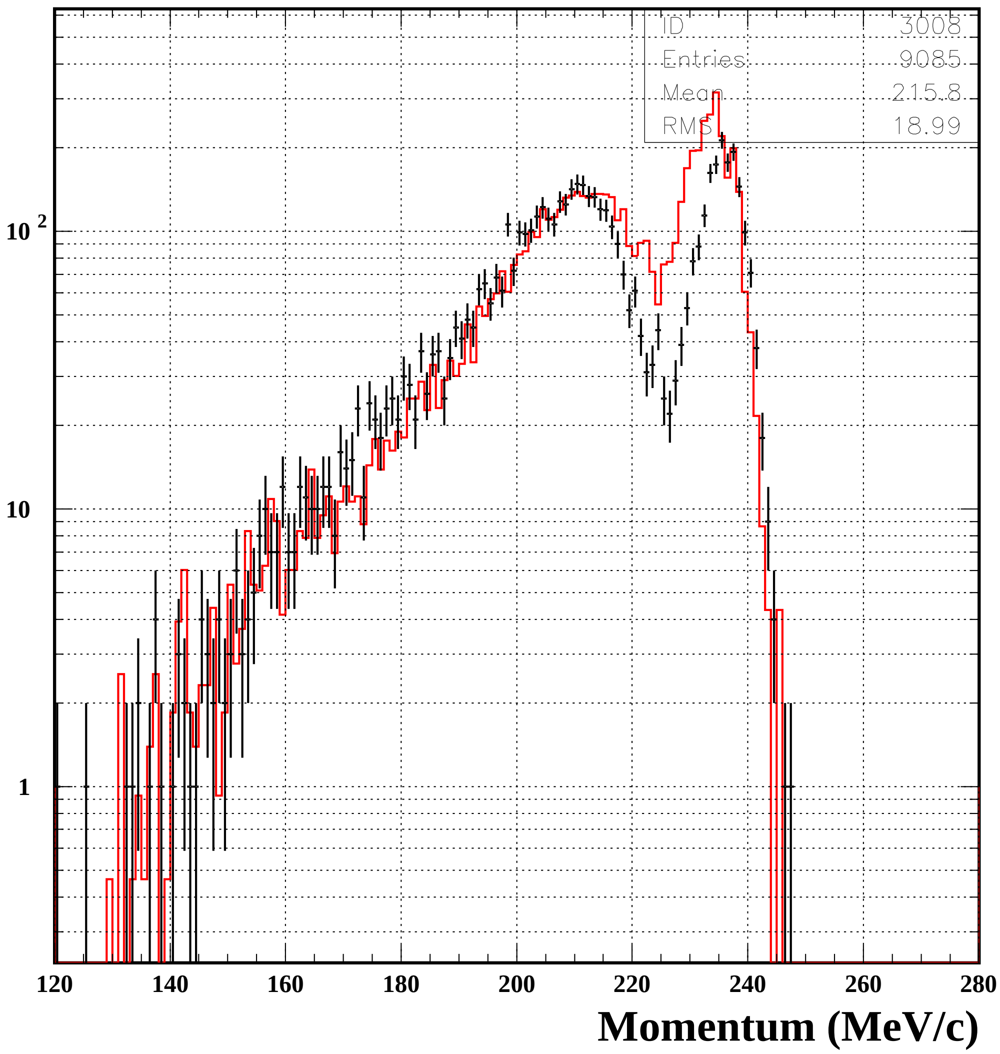

Figure 6: The muon momentum spectra for MC simulated $K_{\mu\nu\gamma} + K_{\mu 2}$ events (red line) and 1/20 of E949 data (black dots) after applying some offline cuts.

compared it with the experimental one. The result is shown in Fig. 6. So the spectra are the same for $p_\mu < 210$ MeV/c and our suggestion that $K_{\mu\nu\gamma}$ is the dominant background source is a true, but there is a discrepancy between MC simulated muon momentum spectrum and the experimental one for $p_\mu > 210$ MeV/c. This effect is under investigation.

Using MC simulated muon momentum spectrum in the 160 MeV/c–205 MeV/c region we calculated the E949 sensitivity to the $K^+\mu^+\nu_H$ branching ratio. For example, if $BR(K^+\mu^+\nu_H) = 10^{-6}$ we should expect $\sim 5 \times 10^3$ signal events (initial acceptance is 10^{-3}) and $\sim 2.5 \times 10^3$ background events for heavy neutrino mass $m_{\nu_H} = 250$ MeV. If $BR(K^+\mu^+\nu_H) = 10^{-7}$ we should expect ~ 500 $K^+ \to \mu^+\nu_H$ events with the same acceptance and background events. So we can reach the sensitivity to the $K^+\mu^+\nu_H$ branching ratio $\sim 4 \times 10^{-8}$ (3σ) for $m_{\nu_H} = 250$ MeV. This sensitivity may be increased 2–3 times by offline cuts optimization. Fig.7 shows the current experimental and BBN constrain on $|U_\mu|^2$ and our preliminary result (the gap between red lines). According to this Figure we may exclude the heavy neutrino existence with mass below ~ 160 MeV.

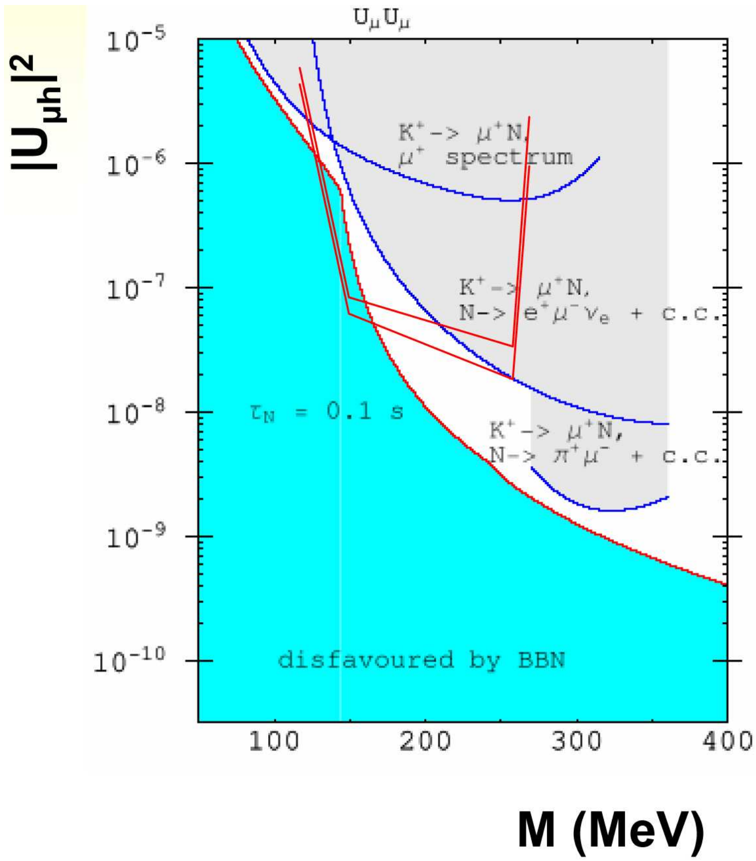

Figure 7: Limits on $|U_\mu|^2$ depending on heavy neutrino mass from BBN (lower bound) and from direct searches in the CERN PS191 experiment and rare kaon decays experiment (upper bounds). The gap between red lines is preliminary result of this analysis.

4 Conclusion

The νMSM model predicts the heavy neutrino existence with mass in the $\mathcal{O}(1)$ GeV region. To study mass region $M_\pi < m_{\nu_H} < M_K$ there was suggested to use E949 data. The expected sensitivity to the $BR(K^+ \to \mu^+\nu_H)$ is about 10^{-7}–2×10^{-8} and depends on heavy neutrino mass. It is also possible to exclude the heavy neutrino existence with mass below ~ 160 MeV.

References

[1] S. Fukuda et al., Phys. Rev. Lett. **81**, 1562 (1998)

[2] Q.R. Ahmad et al., Phys. Rev. Lett. **89**, 011301 (2002)

[3] M.H. Ahn et al., Phys. Rev. D **74**, 072003 (2006)

[4] P. Adamson et al., Phys. Rev. Lett. **101**, 221804 (2008)

[5] K. Eguchi et al., Phys. Rev. Lett. **90**, 021802 (2003)

[6] M. Apollonio et al., Eur. Phys.J. C **27**, 331 (2003)

[7] T. Asaka, M. Shaposhnikov, Phys. Lett. B **620**, 17 (2005)

[8] A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, Ann.Rev.Nucl.Part.Sci. **59**, 191 (2009)

[9] D. Gorbunov, M. Shaposhnikov, JHEP, **0710:015**, (2007)

[10] R. E. Shrock, Phys. Lett. D **24**, 1232 (1981)

[11] T. Yamazaki *et al.,* in *Proceedings of High Energy Physics, vol.1, Leipzig, 1984*, p.262.

[12] M. Daum et al., Phys. Rev. Lett. **85**, 1815 (2000)

[13] G. Bernardi et al., Phys. Rev. Lett. B **203**, 332 (1988)

[14] A.D. Dolgov et al., Nucl.Phys. B **590**, 562 (2000)

[15] Andrzej J. Buras, Felix Schwab, Selma Uhlig, Rev.Mod.Phys. **80**, 965-1007 (2008)

[16] E949 collaboration, Phys.Rev.D **79**, 092004 (2009)

[17] B. Bhuyan et al., E949 TN-K025 (2004)

[18] S. Adler et al., Phys. Rev. D. **77**, 052003 (2008)