Search for heavy neutrino in kaon decays

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Abstract

The existence of a heavy neutrino, ν_H, in the $K^+ \to \mu^+\nu_H$ decays was tested using the E949 experimental data with an exposure of 1.70×10^{12} stopped kaons. The allowed heavy neutrino mass region for the analysis is from 175 MeV/c^2 to 300 MeV/c^2. With major background from the radiative $K^+ \to \mu^+\nu_\mu\gamma$ decay understood and suppressed, the preliminary new upper limits (90% C.L.) on the neutrino mixing matrix element between muon and heavy neutrino, $|U_{\mu H}|^2$, were set at the level of 10^{-8} to 10^{-9}.

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 [?] 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) [?, ?]. 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. 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 ~ 150 MeV to ~ 100 GeV and should be degenerate ($\Delta M_{2,3} \ll M_{2,3}$) to generate baryon asymmetry of the Universe.

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 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 [?]:

$$\Gamma(M^+ \to l^+\nu_H) = \rho\Gamma(M^+ \to l^+\nu_l)|U_{lH}|^2, \tag{1}$$

where $M = \pi$, K; $l = e$, μ; ρ is a kinematical factor and lies in the range from 1 to 4 for $0 < m_{\nu_H} < 300$ MeV. This strategy have been used in a number of experiments for the search of neutral leptons in the past [?, ?, ?, ?], where the spectra of electrons and muons originating

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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 [?, ?, ?, ?, ?, ?, ?, ?].

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

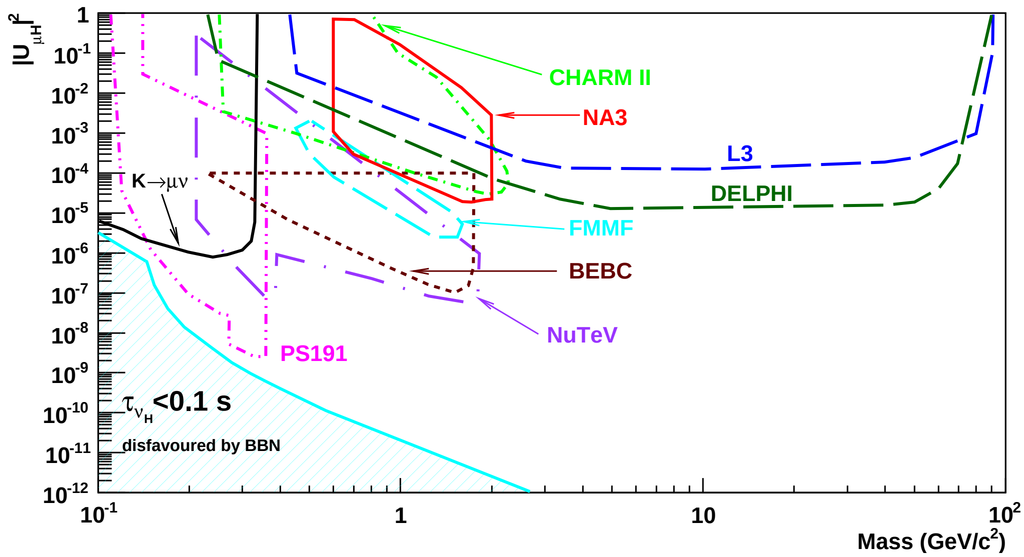

Figure 1: Limits on $|U_{\mu H}|^2$ versus heavy neutrino mass in the mass range 100 MeV/c^2–100 GeV/c^2. The area with the solid (black) contour labeled $K \to \mu\nu$ is excluded by production searches [?]. The bounds by decay searches indicated by contours labeled by PS191 [?], NA3 [?], BEBC [?], FMMF [?], NuTeV [?] and CHARMII [?] are at 90 % C.L., while DELPHI [?] and L3 [?] are at 95 % C.L. and are deduced from searches of visible products in heavy neutrino decays. The shaded region shows one of the possible lower bounds from Big Bang Nucleosynthesis [?, ?].

In this paper, we present the preliminary result of a search for heavy neutrinos in $K^+ \to \mu^+\nu_H$ decays from the inclusive muon spectrum of $K^+ \to \mu^+ + nothing$ decays using the kaon decay-at-rest data from the E949 experiment [?].

2 E949 experiment

The E949 K^+ beam was produced by a high-intensity proton beam from the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). Protons were accelerated to a momentum of 21.5 GeV/c and hit a platinum production target.

The E949 detector is shown in Fig. 2. The coordinate system of the detector is defined such that the origin is at the center of the target; the $z-$axis is along the beam direction; and the $x-$axis and $y-$axis are set in the horizontal and vertical directions, respectively.

Incoming 710 MeV/c kaons with 3/1 K^+/π^+ ratio are identified by Čerenkov counter and two proportional wire chambers then slowed down by an inactive degrader and an active degrader (AD), 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.

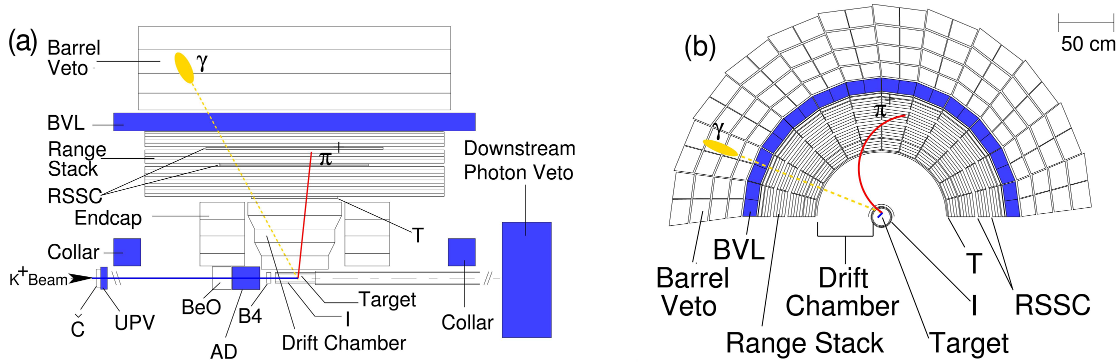

Figure 2: Schematic side (a) and end (b) views of the upper half of the E949 detector. An incoming kaon is shown traversing the beam instrumentation stopping in the target and decaying to $\pi^+\pi^0$. The outgoing charged pion and one photon from $\pi^0 \to \gamma\gamma$ decay are illustrated.

The detection of any activities coincident with the charged track is very important for suppressing the backgrounds for $K^+ \to \mu^+\nu_H$ 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.

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). That's why we decided to use the main E949 trigger. This trigger consists of several requirement:

1. K^+ stop requirements. A kaon must enter the target; this was checked by coincidence of the kaon Čerenkov detector, the B4 hodoscope and the target with at least 20 MeV energy deposit. To be sure that the kaon decays at rest, the secondary charged particle must hit the IC at least 1.5 ns later than the kaon hit in the Čerenkov detector.

2. 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.

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

4. Online pion identification. 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 few mm) and rarely goes out of the stopping counter. So pulses in the stopping counter recorded by the transient digitizers (TDs) have double-pulse structure up to ~ 70 ns. The single-pulse events were rejected.

5. Online photon veto. Events were rejected if any activity in the BV, BVL or EC with energy above a threshold was detected. This condition removed events with photons. A similar requirement in the RS is also applied. The 24 sectors of the RS are conventionally grouped into six; a group of 4 sectors is called a "hextant". Only one hextant is allowed to have hits or two hextants if they are adjacent. This rejects events with multiple tracks and events with photon activity in the RS.

The range in a plastic scintillator and the momentum of the charged particles for events that pass E949 trigger is shown in Fig. 3. Events in the muon band are due to multi-body decays, such as $K^+ \to \mu^+\nu_\mu\gamma$ ($K_{\mu\nu\gamma}$), $K^+ \to \mu^+\pi^0\nu_\mu$ ($K_{\mu 3}$), 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,

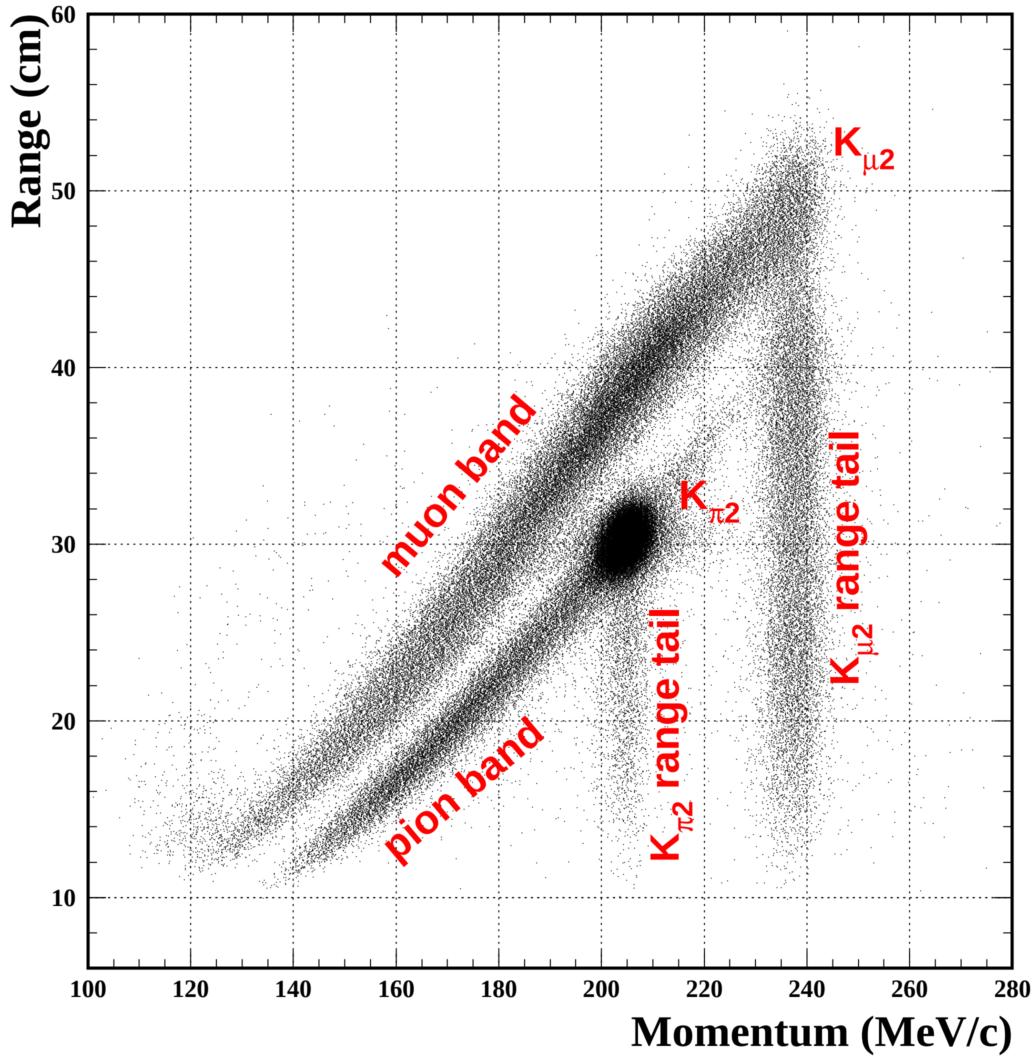

Figure 3: Range in a plastic scintillator and the momentum of the charged particles for events that pass E949 trigger.

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.

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

3 Data Analysis

3.1 Total acceptance

In addition to trigger requirement we used several groups of offline cuts to select single muon track. The kinematic cuts were used to select events in the detector fiducial volume. Beam cuts were applied to identify incoming particle as a kaon and suppress extra beam particles at the track time. To suppress kaon decay-in-flight we applied delay coincidence cut. Numerous requirement were placed in on the activity in the target to suppress background and ensure reliable determination of the kinematic properties of the charged muon. Range-momentum cut was changed to select muons while in E949 analysis it was designed to check whether the range of a charged track is consistent with that for pions. To suppress photon activity in the detector we applied photon veto cut (loose for the background study and tight for the final result). The track quality cuts (UTCQUAL and PRRF) were also applied.

Acceptance for the $K^+ \to \mu^+\nu_H$ decay was measured using Monte-Carlo simulation and monitor triggers.

Muon momentum spectra after each group of offline cuts and total acceptance are shown in Fig. 4. The single event sensitivity (S.E.S.) for the heavy neutrino with mass $m_{\nu_H} = 250$ MeV/c^2

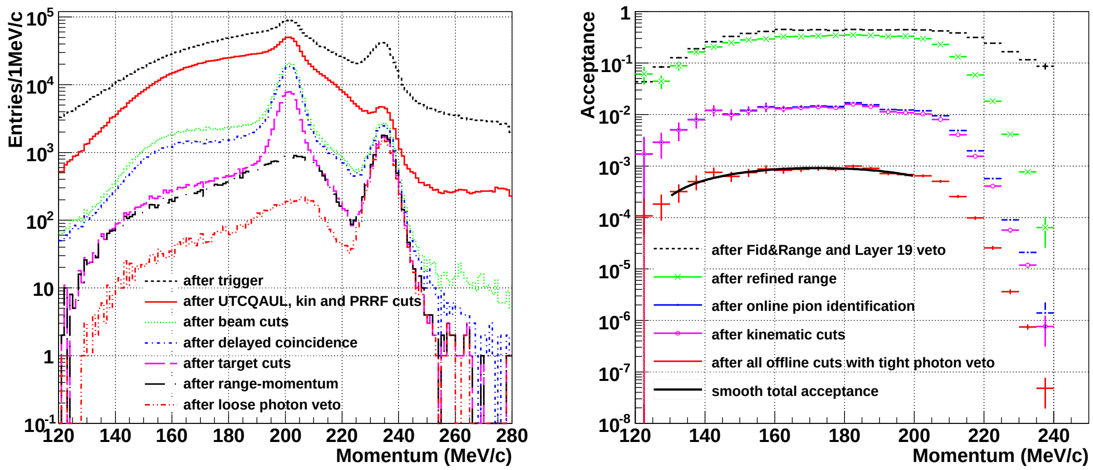

Figure 4: (Left) Momentum spectra based on the 1/20 data sample after applying each group of cuts. (Rigth) Acceptance dependence on momentum. Black solid line shows the smooth total acceptance which is used for the mixing matrix element upper limit calculation.

can be calculated as

$$S.E.S. = \frac{1}{Acc \times N_K} = 7.35 \times 10^{-10}, \tag{2}$$

where Acc is the total acceptance and N_K is the total number of stopped kaons. This sensitivity is roughly constant for the whole investigated region.

To verify our acceptance measurement we calculated $K_{\mu 2}$ and $K_{\mu\nu\gamma}$ branching ratios. The $K_{\mu 2}$ branching ratio was measured to be 0.54 ± 0.15 and it is consistent with PDG value (0.6355 ± 0.0011) within the error [?]. The $K_{\mu\nu\gamma}$ branching ratio was measured to be $(1.3 \pm 0.4) \times 10^{-3}$ for $140 < p_\mu < 200$ and is also consistent with PDG value $((1.4 \pm 0.2) \times 10^{-3})$ for the same muon momentum region [?].

3.2 Residual background

The search for $K^+ \to \mu^+\nu_H$ is to find additional peak below $K_{\mu 2}$ peak. So we should well understand all background sources that can fake or cover our signal. We simulated the main background sources, $K_{\mu\nu\gamma}$, $K_{\mu 3}$ and $K_{\pi 2\gamma}$ decays. After trigger requirements and offline selection criteria 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 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.

Given the agreement between the PDG values and our $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \mu^+\nu_\mu\gamma$ branching ratio measurements, the experimental muon momentum spectra and the simulated

$K_{\mu 2} + K_{\mu\nu\gamma}$ muon momentum spectra can be compared. To add $K_{\mu 2}$ and $K_{\mu\nu\gamma}$ decays together we take into account their branching ratios and the number of simulated events. The momentum dependence of acceptance after all cuts and comparison between experimental (5% all data) and simulated muon momentum shape are shown in Fig. 5. There are some discrepancies between

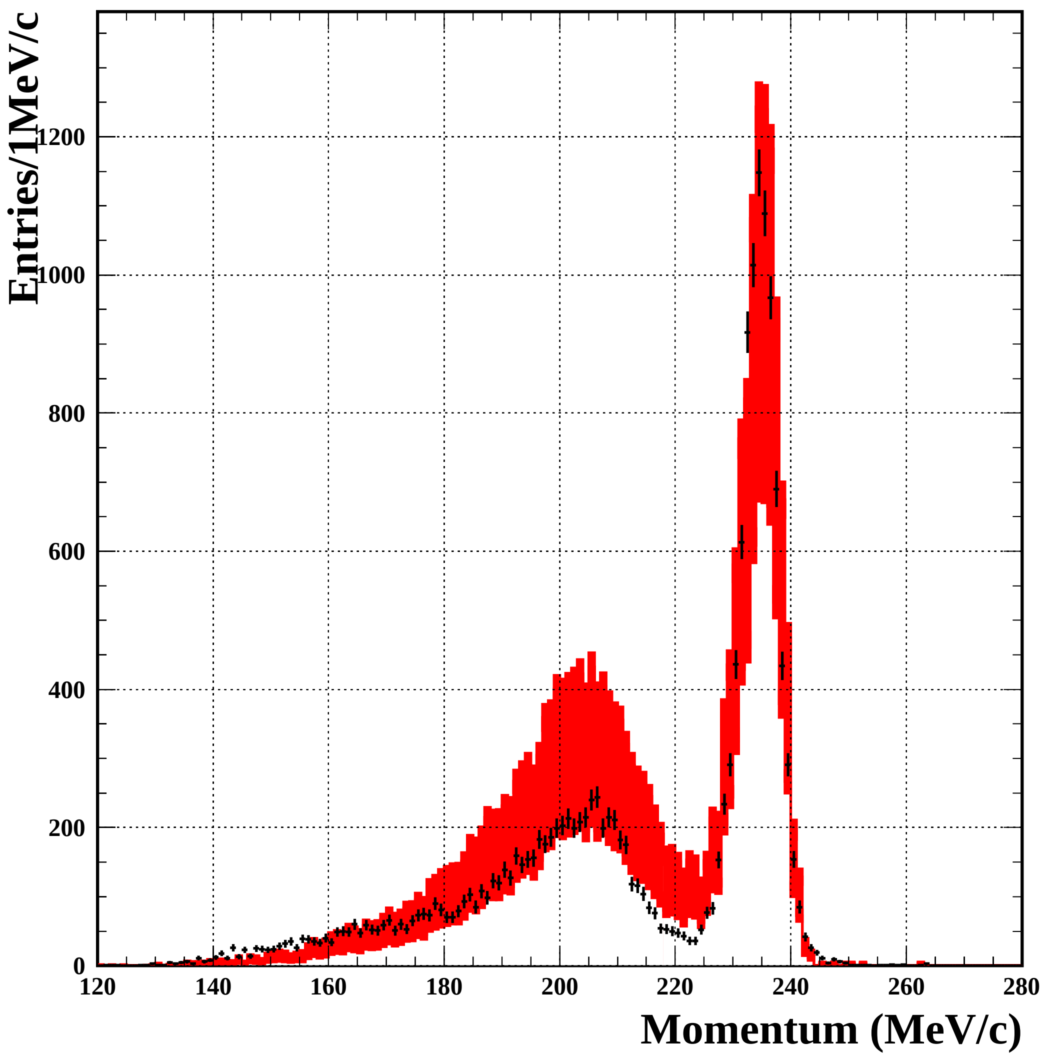

Figure 5: Comparison between experimental (5% all data) and simulated $K_{\mu 2} + K_{\mu\nu\gamma}$ decays.

data and MC in the muon momentum spectrum. Between 200 MeV/c and 220 MeV/c, the radiative gamma energy is low, the difference is caused by the difficulty in simulating detector activity or electronic noise of the low photon veto cut threshold. Beyond 220 MeV/c, it is caused by the uncertainty of layer 19 and refined range cuts.

Below 200 MeV/c, the simulated and experimental spectra are consistent. Since the simulated shape does not show obvious bumps or valleys, we assume that the experimental background shape is also smooth.

3.3 Results

To search for additional peaks below the main $K_{\mu 2}$ peak we used asymptotic formula for the distribution of a test statistic, which was derived using the results of Wilks and Wald [?]. The method is a frequentist approach which is free of computationally expensive Monte Carlo calculations and is able to consider the shape of the signal. It thus avoids the ambiguity of selecting a signal region. Besides the mean value of the upper limit, an error band of the upper limit can be also calculated. The main feature of this approach is Asimov data set. An Asimov data set was used to evaluate the expected upper limit and its error band. For the heavy neutrino searching in this paper, the Asimov data set is the background-only expectation assuming no heavy neutrino signal in the region under test. The background shape was determined directly by fitting the momentum spectrum of data after all criteria. To avoid artificial peaks or valleys in the signal region, the range $\pm 6\sigma$ (the σ is the momentum resolution which is known from MC simulation) around the point of interest was chosen to fit for background with a second order polynomial function. With known background shape we are able to estimate expected number of background events in each bin in the testing region.

The muon momentum spectrum for the full data sample after all cuts and peak search result are shown in Fig. 6.

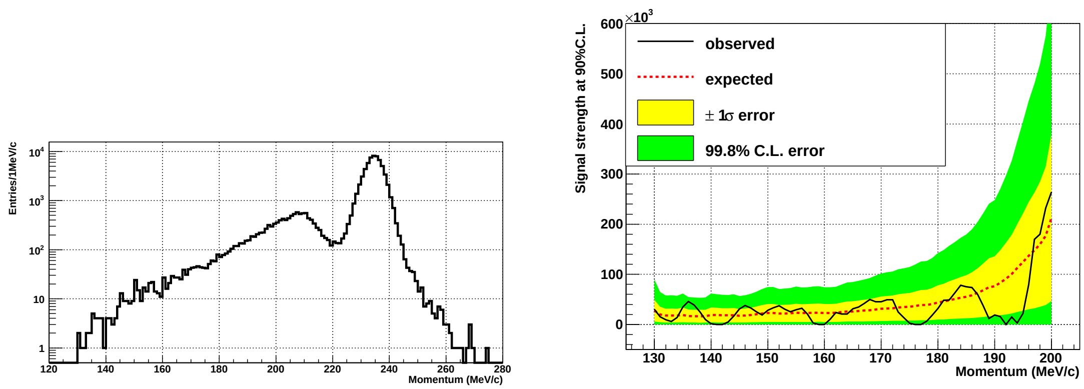

Figure 6: (Left) Muon momentum spectrum for the full data after all cuts applied. (Right) 90%C.L. expected upper limit with a $\pm 1\sigma$ error band and 99.8% C.L. error band. The black line is the observed upper limit result.

Since the observed upper limit is within the error band of the expected upper limit there is no evidence for a heavy neutrino signal.

The preliminary upper limit on mixing matrix element $|U_{\mu H}|^2$ set by this experiment is shown in Fig. 7.

4 Conclusion

The preliminary result of the search for heavy neutrinos in the $K^+ \to \mu^+ \nu_H$ decay channel using the E949 data sample in an exposure of 1.70×10^{12} stopped kaons is presented. Since no evidence for extra peaks below the main $K^+ \to \mu^+ \nu_\mu$ peak was found we set preliminary upper bounds on the mixing matrix element $|U_{\mu H}|^2$ in the mass region 175–300 MeV/c^2. In contrast to the CERN PS191 or BBN bounds our result is model-independent because we did not make any assumptions about heavy neutrino decay rates or couplings.

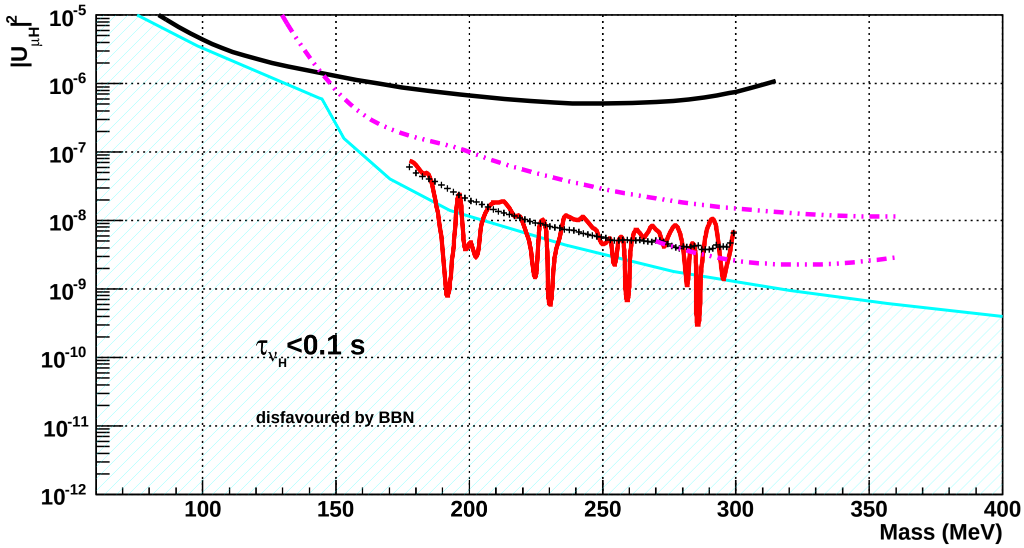

Figure 7: The preliminary upper limits on the mixing matrix element $|U_{\mu H}|^2$ set by this experiment (solid red curve, black crosses show expected upper limit) and others. Solid smooth black line shows the result of the peak search in kaon decays [**?**], dotted black lines show the results of the heavy neutrino decay experiment CERN PS191 [**?**] in two modes: top dotted line is derived from $K^+ \to \mu^+\nu_H \to \mu^+(\mu^- e^+ \nu_e) + c.c.$, bottom dotted line is derived from $K^+ \to \mu^+\nu_H \to \mu^+(\mu^-\pi^+) + c.c.$ The shaded region shows one of the possible BBN lower bounds [**?**, **?**].