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Overview of the sterile neutrino searches and status of SBN/ICARUS experiment

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The results of short-baseline oscillation experiments have raised the possibility of the existence of light sterile neutrino states in the eV mass range. As a result, there has been a surge in new experimental efforts to definitively approve or disapprove the oscillations between active and sterile neutrino states. This new neutrino, if confirmed, would be a Standard Model gauge singlet, hence dubbed "sterile". The discovery or exclusion of this sterile neutrino could have far-reaching implications for particle physics, as well as astrophysics and cosmology. In this proceedings, I provide an overview of the ongoing searches for sterile neutrinos and discuss the progress and plans for the ICARUS and SBND experiments as part of the Short-Baseline Neutrino program at Fermilab.

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1. Introduction:

Neutrino oscillation experiments have progressed significantly since its initial discovery, and the standard three-flavor neutrino oscillation model is now well established, with most parameters measured with considerable precision. While neutrino oscillation is undoubtedly the primary explanation for flavor conversion that accounts for solar, atmospheric, reactor, and accelerator observations, we must also consider the potential for additional effects beyond the standard model (BSM) at a sub-leading level.

Recently, a series of observations have indicated anomalies that deviate from the three-neutrino framework. Many of these anomalies are primarily associated with electron neutrinos and have been detected from sources of electron and muon neutrinos using either Cherenkov or scintillator detectors, often at relatively short distances from the various neutrino sources.

The idea of the light sterile neutrino was initiated in view of the results from the LSND experiment[1] which reported a signature of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at 3.8σ. Later MiniBooNE[2] experiment with the same L/E ratio also confirmed this result at 4.8σ significance. If we want to interpret these results through effective two flavour oscillations then corresponding to $L/E \sim 1$ GeV/km in these experiments, there should be a new mass-squared difference $\Delta_{sm} \sim 1$ eV^2. This new mass-squared difference doesn't fit in the standard three flavour oscillation scheme requiring one to incorporate at least one extra neutrino with a mass of eV scale.

Recent support for the existence of an additional light sterile neutrino has come from the observation of an electron neutrino (ν_e) deficit in gallium-based radiochemical experiments, specifically the SAGE[3] and GALLEX[4] experiments, referred to as the Gallium anomaly. This finding has been bolstered by recent results from the BEST[5] experiment, which reported a significance of 5σ. Additionally, there has been a reactor antineutrino anomaly where several reactor neutrino experiments indicated a deficit in the measured flux, particularly after updated calculations of the inverse beta decay cross-section. These anomalies could also be attributed to a sterile neutrino with a mass on the order of eV. So far, the 3+1 framework, which incorporates a light sterile neutrino with a mass of 1 eV, provides the most economical explanation for these anomalies. However, this framework encounters challenges due to tensions between the disappearance and appearance data of neutrinos (ν_μ).

From a theoretical perspective, the existence of sterile neutrinos is an intriguing outcome of neutrinos having a non-zero mass. As gauge singlets, they lack a predetermined mass scale, which invites curiosity about their nature. Understanding neutrino masses often requires introducing new, yet-to-be-observed particles, making the neutrino sector a promising frontier for discovery. Many models imply fascinating deviations from the Standard Model, suggesting a vibrant array of phenomena. In particular, new particles or gauge interactions associated with neutrinos could significantly influence experiments, potentially affecting oscillation phenomena or leading to the production of novel particles in beams and detectors. This rich landscape makes the study of sterile neutrinos both compelling and essential for deepening our understanding of the universe.

The framework of light sterile neutrino oscillations can theoretically explain all the short-baseline experimental anomalies observed so far. However, it does not account for the absence of corresponding oscillations seen in long-baseline and atmospheric neutrino measurements. This discrepancy has prompted the need to interpret compelling experimental results, leading to an

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extensive neutrino research program. Additionally, a substantial body of related phenomenological work has emerged, presenting various viable interpretations ranging from modifications of three-flavor neutrino mixing to potential interactions with hidden sectors.
As the question of light sterile neutrino oscillations is further explored over the next several years, the Short-Baseline Neutrino Program (SBN) Program[6] at Fermilab is designed to investigate the possibility of sterile neutrinos in the O(1 eV) mass region and provide the required clarification of the anomalies. In particular, SBN will allow for a very sensitive search for $\nu_\mu \approx \nu_e$ appearance signals, covering the LSND 99% C.L. allowed region at $\approx 5\sigma$ C.L.

2. Experimental anomalies leads to the sterile hypothesis:

Over the past decade, four persistent anomalies in the neutrino sector have motivated the development of an active short-baseline neutrino program. Two of these anomalies stem from the unexpected oscillatory appearance of electron (anti)neutrinos in relatively pure muon (anti)neutrino beams. These beams originate from the decay of charged pions, both at rest and in flight. The other two anomalies relate to a discrepancy between the expected and observed normalization of electron (anti)neutrinos from conventional fission reactors and the radioactive decay of Gallium-71. In these instances, while no oscillatory signature is detected, the overall normalization deficit can be attributed to rapid oscillations occurring at a high mass-squared difference (Δm^2). These rapid oscillations are averaged out, resulting in an apparent overall deficit.

3. Current status of 3+1 light sterile neutrino :

In the simplest 3+1 model, the standard neutrino sector is extended by an extra neutrino flavor ν_s which is a gauge singlet and does not experience weak interactions. The three neutrino flavors and the sterile neutrino are admixtures of four neutrino mass eigenstates m_4, where $m_4 \approx$ 1eV, motivated by the LSND and MiniBooNE experiments. For the 3 + 1 oscillation framework, the new mixing matrix U will have three additional mixing angles $\theta_{14}, \theta_{24}, \theta_{34}$ corresponding to mixing between the extra light sterile neutrino ν_s and the active sector neutrinos along with two new CP phases δ_{14}, δ_{34} and can be expressed as follows,

$$U = \tilde{R}_{34}(\theta_{34}, \delta_{34}) R_{24}(\theta_{24}) \tilde{R}_{14}(\theta_{14}, \delta_{14}) * R_{23}(\theta_{23}) \tilde{R}_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12}) \quad (1)$$

where $\tilde{R}_{ij} = U^{\delta}_{ij}(\delta_{ij}) R_{ij}(\theta_{ij}) U^{\dagger\delta}_{ij}(\delta_{ij})$, $R_{ij}(\theta_{ij})$'s are rotational matrices in i-j plane and $U^{\delta}_{ij} = diag(1, 1, 1, e^{\iota\delta_{ij}})$ with δ_{ij}'s being the CP phases.
The current status of the 3+1 model can be best understood thorough global analysis. This approach allows each of the various short-baseline experiments to contribute to a cohesive statistical framework, leveraging the strength of their individual results. All experimental searches show a strong preference for the 3+1 model over the Standard Model, primarily due to findings from the LSND and MiniBooNE experiments. However, there is a notable tension among the different datasets that has been consistently observed. As shown in Figure 1, the preferred regions within the parameter space of the 3+1 model are illustrated for several short-baseline appearance experiments. The left panel displays the combined results of all experiments at a 99% confidence level (CL) for two degrees of freedom. In contrast, the right panel highlights the regions favored by all short-baseline

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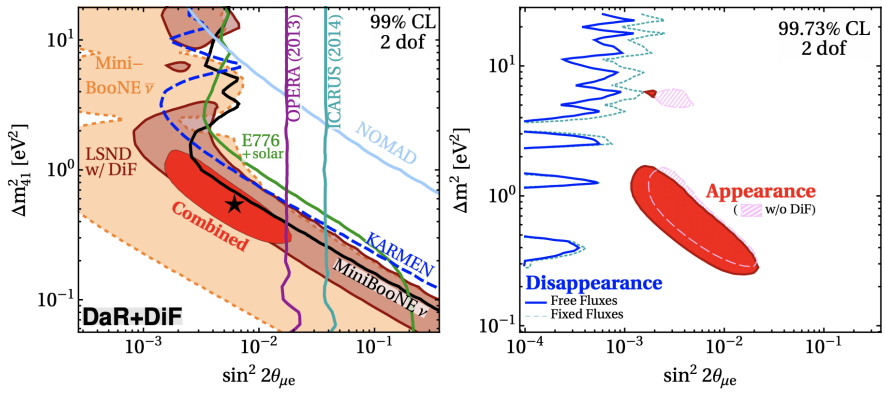

Figure 1: Left: Preferred regions by several $\nu_\mu \rightarrow \nu_e$ appearance experiments in the 3+1 scenario at 99% CL for 2 degrees of freedom. Right: Preferred region of short-baseline appearance experiments (red region), compared to the region excluded by disappearance experiments (blue line) at 99.73% CL for 2 degrees of freedom. The figure taken from [7]

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appearance experiments, marked in red, and compares them to the excluded region identified by all disappearance experiments, indicated by the blue line, at a 99.73% confidence level (CL) for two degrees of freedom. It is important to note that the area to the right of the blue line is excluded, which encompasses the entire allowed appearance region.

4. Future experimental prospects : The SBN/ICARUS experiment

The Short Baseline Neutrino (SBN) program[6] aims to investigate the existence of sterile neutrinos comprehensively. Additionally, it seeks to conduct world-class cross-section measurements and searches for beyond-the-standard-model (BSM) physics, all while advancing liquid-argon neutrino technology for the future Long Baseline Neutrino program. This program features a multi-detector facility utilizing the Booster Neutrino Beam (BNB) at Fermilab, where all detectors employ the same accelerator beam, nuclear target, and detector technology. This approach is designed to minimize systematic uncertainties to the percentage level. The neutrino beam, which was also utilized by the MiniBooNE experiment, is generated from pions that decay in flight. The technology employed for the three detectors includes Liquid Argon Time Projection Chambers (LArTPC). MicroBooNE, located 470 meters from the source and near the MiniBooNE experiment site, was the first LArTPC in the BNB program and used 170 tons of liquid argon. It completed data collection in 2021 and is currently processing its entire dataset. Preliminary results based on half of the data have been published, showing no evidence of low-energy excess. However, the measurement's significance was not sufficient to conclusively eliminate the sterile neutrino hypothesis. The SBN's far detector, ICARUS, is currently collecting data at a distance of 600 meters from the neutrino source, utilizing 760 tons of liquid argon. For a comprehensive oscillation analysis, a near detector is necessary close to the neutrino source. The Short Baseline Near Detector (SBND), positioned 110 meters from the neutrino beam source, uses 260 tons of liquid argon.

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5. The ICARUS detector

The LArTPC technology has seen significant development over the past thirty years, primarily through the efforts of the ICARUS Collaboration[8]. The ICARUS-T600 cryogenic detector is the largest LArTPC ever constructed, with a cryostat that contains 760 tons of liquid argon (LAr). Today, the ICARUS-T600 represents the pinnacle of LArTPC technology and marks a major milestone in the practical implementation of large-scale liquid argon detectors. The ICARUS-T600 detector[9] consists of two large identical modules with internal dimensions 3.6m × 3.9m × 19.6m filled with 760 tons of ultra-pure liquid argon, surrounded by a common thermal insulation. Each module houses two TPCs separated by a common central cathode for an active volume of 3.2 m x 2.96m x 18.0 m. A uniform electric field (E = 500 V/cm) is applied to the drift volume. Each TPC is made of three parallel wire planes, 3 mm apart, with 3 mm pitch, facing the drift path (1.5 m) and with wires oriented at 0,0, 60 deg with respect to the horizontal direction, respectively. By appropriate voltage biasing, the first two signal sensing planes (Induction-1 and Induction-2) provide induced signals in a non-destructive way, whereas the last Collection plane finally collects the ionization charge.

The ICARUS-T600 light detection system consists of 360 8" Hamamatsu R5912-MOD PMTs deployed behind the four TPCs, 90 PMTs each. Since the PMT glass is not transparent to the 128-nm wavelength scintillation light produced in liquid argon, each unit is provided with a $\approx$ 200 $\mu g/cm^2$ coating of tetra-phenyl butadiene (TPB), to convert the VUV photons to visible light. ICARUS-T600 based at FNAL faces more challenging experimental conditions than at LNGS: due to its shallow depth operation, identification of neutrino interactions among 11 kHz of cosmic rays is required. 4π coverage Cosmic Ray Tagger (CRT) has been conceived with the primary function of tagging muons passing through or near the ICARUS cryostats. The ICARUS CRT consists of a top, side and bottom subsystem.

6. Commissioing and performance of the ICARUS detector

After a significant overhaul at CERN and INFN laboratories, the ICARUS detector was shipped to Fermilab in 2017 and deployed at a shallow depth, surrounded by the Cosmic Ray Tagger (CRT) and protected from cosmic rays by a 2.8-meter-thick layer of concrete. ICARUS completed its commissioning phase in 2022 and began operating in physics mode in June 2022 (RUN1), collecting neutrinos from the BNB and NuMI beams. This was triggered by the photomultiplier signals coinciding with beam spills. The ICARUS Collaboration has made significant investments to enhance detector performance following the initial operation. Several improvements were implemented during the beam summer shutdowns in 2022, 2023, and 2024. Throughout this data collection period, the liquid argon was maintained at very high purity levels, achieving an electron lifetime exceeding 6 ms during Runs 2 and 3. To date, ICARUS has completed three physics runs, collecting a total of 3.82×10^{20} Protons On Target (POT) using Forward Horn Current (FHC) with the Booster Neutrino Beam (BNB), and 3.42×10^{20} POT in FHC and 3.82×10^{20} POT using Reverse Horn Current (RHC) with the NuMI beam respectively.

One of the initial measurements performed was the free electron lifetime, denoted as τ_{ele}. This parameter is essential for monitoring the conditions of liquid argon in the time projection chambers

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(TPCs) and for achieving precise measurements of energy deposition from the ionization charge signal in the recorded events. The steady-state values of τ_{ele} exceeded 3 ms in both cryostats. The data collected by the detector are processed using offline software to extract the necessary information for reconstructing and analyzing events. The signal reconstruction process from the TPC wires and photomultiplier tubes (PMTs) follows a logic similar to that employed in other liquid argon time projection chamber (LArTPC) experiments. Overall, the efficiency of identifying a wire signal and associating it with the corresponding track exceeds 90% across all three wire planes. Additionally, the reconstruction of scintillation light associated with the event of interest relies on the signals recorded by the PMTs, which are sampled at a rate of 500 MHz.

Figure 2: Deployment of the ICARUS cryostats inside the pit of the SBN Far Detector experimental hall at Fermilab in August 2018 (left). Installation of TPC, PMT and laser feed-through flanges in December 2018 (center). Status of the ICARUS detector at the beginning of data taking for commissioning (right). Figure taken from [9].

The initial ICARUS trigger system utilizes the coincidence of the BNB and NuMI beam spills, which are , 1.6 μs and 9.6 μs long, respectively, along with the prompt scintillation light detected by the PMT system located behind the wire planes of each TPC. To assess the general behavior of the detector, a visual study was conducted to select and identify neutrino interactions within the active liquid argon using a graphical event display. As a first step, all events recorded during the BNB and NuMI beam runs were analyzed by selecting the tracks within the cryostat where the trigger signal had been generated. An example of a ν_μCC (muon neutrino charged current) candidate is shown in Figure 3a, which has an estimated total deposited energy of approximately 1.1 GeV. The charged current muon candidate measures 3.8 meters in length, while a highly ionizing track identified from the primary vertex corresponds to a 20 cm long proton track. Similary, a ν_eCC (electron neutrino charged current) candidate from NuMI beam is shown in Figure 3b.

7. Event selection for the sterile neutrino searches and physics program of the SBN:

The data collected by the ICARUS experiment prior to the commencement of the joint operation with SBND is being utilized for a comprehensive standalone search program that includes both the BNB and NuMI off-axis beams. This program encompasses the verification of the recent claim regarding a new sterile neutrino made by the NEUTRINO-4 experiment. Additionally, these datasets are valuable for the joint SBN program and facilitate the development of simulation and automatic event reconstruction tools that are shared with SBND. Currently, the BNB dataset is focused on a single detector search for ν_μ disappearance, while the data collected from NuMI is being used

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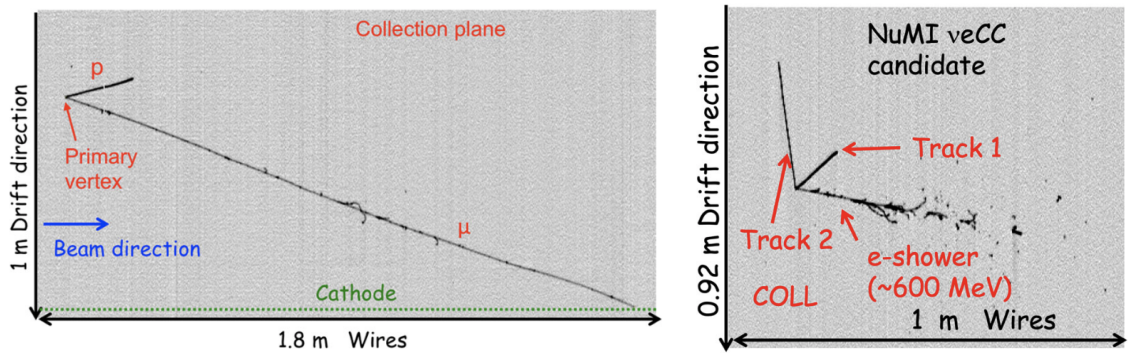

(a) ν_μCC events from BNB beam

(b) ν_eCC events from NuMI beam

Figure 3: Left: ν_μCC events from BNB beam and Right: ν_eCC events from NuMI beam. Figure taken from [9].

for ν_μ cross-section measurements and investigations into phenomena beyond the Standard Model (BSM).

The analysis of quasi-elastic-like collected events is progressing well. This analysis is being expanded to include neutrino-electron charged-current (ν_eCC) events, as well as non-contained muon-neutrino charged-current (ν_μCC) interactions that result in more complex final states. These interactions are particularly interesting at high energy for the off-axis NuMI beam data. ICARUS can also directly evaluate the claims made by NEUTRINO-4 by measuring ν_e disappearance in the approximately 5% ν_e enriched off-axis NuMI beam. In addition to searching for anomalous ν_e appearance in the Booster Neutrino Beam (BNB) within the Short Baseline Neutrino program (SBN), the ICARUS measurement of NuMI ν_e disappearance can help resolve a degeneracy between appearance and disappearance measurements in the BNB, significantly enhancing sensitivity in certain regions of the mixing angle phase space. Figure 4 presents the neutrino energy reconstruction on the left and the total transverse momentum distribution on the right, based on 10% of the data and Monte Carlo (MC) samples. ICARUS is expected to conduct high-precision measurements of ν_μ

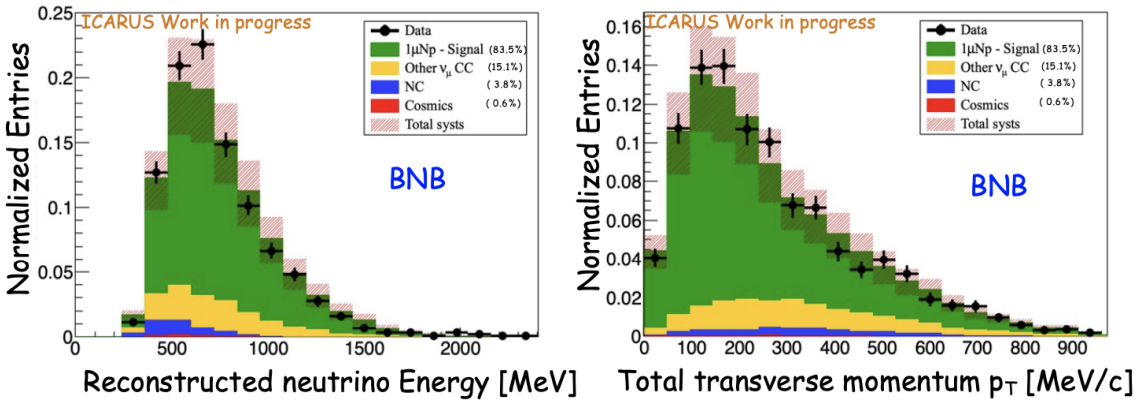

Figure 4: Data and MC comparison of the reconstruction of the neutrino energy (left) and total transverse momentum (right) of neutrino event originating from BNB beam using 10% of the data and MC sample.

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and ν_e neutrino cross sections using the off-axis NuMI beam, focusing on a range that is important for the DUNE project. This will provide comprehensive coverage of the relevant phase space for DUNE, particularly concerning the first neutrino oscillation peak. These measurements will help refine event generators ahead of the DUNE near detector operations. The data collected while NuMI operated in both positive and negative focusing modes is significant and allows for high-statistics measurements of antineutrino interactions with argon, for which there are currently no published results. Additionally, the search for ν_e disappearance at NuMI—to test the NEUTRINO-4 claim—requires a substantial event statistic collected with the same beam polarity to minimize additional systematic uncertainties related to different beam operations. As it stands, the data collected by ICARUS using the NuMI beam is nearly evenly divided between positive and negative beam focusing modes.

The ICARUS detector is located approximately 800 meters off-axis from the high-energy NuMI beam. Its primary goal is to search for sterile neutrinos at the eV mass scale, but its unique position also allows for exploration of other physics scenarios beyond the Standard Model. The initial analysis targets long-lived particles (LLPs) produced from kaon decays that decay into two muons inside the ICARUS detector[10]. The analysis focuses on di-muon decays within a fiducial volume where both muons are detected. A significant excess in a narrow invariant mass region, consistent with a resonance peak, could indicate the presence of new physics. The results are analyzed using the Higgs portal scalar and heavy axion benchmark models. Figure 5a shows the signal box results, including a scale factor for the ν_μCC-Cohπ background from the fitting region in the inset. A bump hunt search revealed an insignificant excess with a global significance of 0.19σ in the mass range of 0.24 GeV $< M_{\mu\mu} <$ 0.31 GeV. The reconstructed mass of each selected event is noted in Figure 5a. In Figure 5b, model independent limits are presented, illustrating the search's reach regarding the branching ratio, scalar lifetime (τ_S), and scalar mass (M_S). Both charged K^{+-} and neutral K_L^0 contribute to scalar production. The combined branching ratio is plotted for different scalar lifetimes.

8. Conclusions:

The experimental data collected over the past decade are undeniably challenging the simplest theoretical interpretation of anomalies in neutrino physics, specifically the idea of a light sterile neutrino within a 3+1 model. This model posits a single underlying source for the outstanding short-baseline anomalies. The ongoing challenges have motivated theoretical developments aimed at finding a comprehensive solution, as well as a diverse experimental program. Despite significant progress in new experimental measurements and theoretical advancements, the short-baseline experimental neutrino anomalies remain unresolved. The Short-Baseline Neutrino (SBN) Program at Fermilab presents exciting opportunities, particularly with the ICARUS-T600 detector, which serves as the far detector for the SBN program. The ICARUS detector has already collected two years of data, focusing on a sensitive study of the claims made by the Neutrino-4 short-baseline reactor experiment. This study is being conducted in both the ν_μ channel, using the Booster Neutrino Beam (BNB), and in the ν_e channel, with the NuMI beam. Additionally, ICARUS will investigate other fundamental topics, such as neutrino cross sections with the NuMI beam, and will conduct several searches for phenomena beyond the Standard Model. The search for evidence of a sterile neutrino

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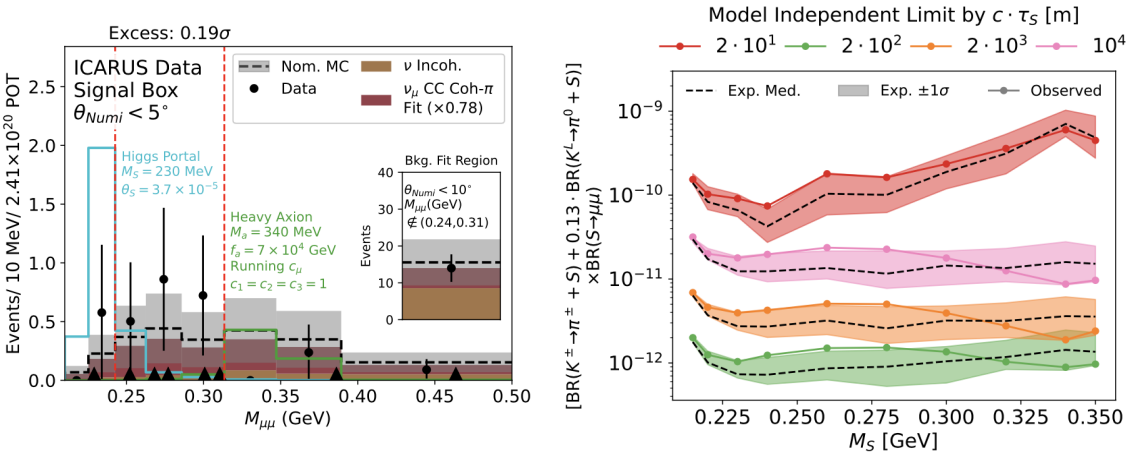

(a) Signal box result of the search

(b) Model independent limits

Figure 5: Left: A scale factor on the ν_μCC-Cohπ background is obtained from a fit region shown in the inset. A bump hunt search in the data against the scaled background prediction obtains an insignificant excess with a global significance of 0.19σ, Right: Model independent limits (at the 90% CL) on the process $K \to \pi + S(\to \mu\mu)$ for a long lived particle S. Figure taken from [10].

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will continue in collaboration with the Short-Baseline Near Detector as part of the Short-Baseline Neutrino program.

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