Latest long-lived HNL and HPS results from MicroBooNE

LLP12 workshop

Luciano Arellano

on behalf of the MicroBooNE collaboration

Nov 2, 2022

Overview

The MicroBooNE experiment

Heavy Neutral Leptons and Higgs Portal Scalars

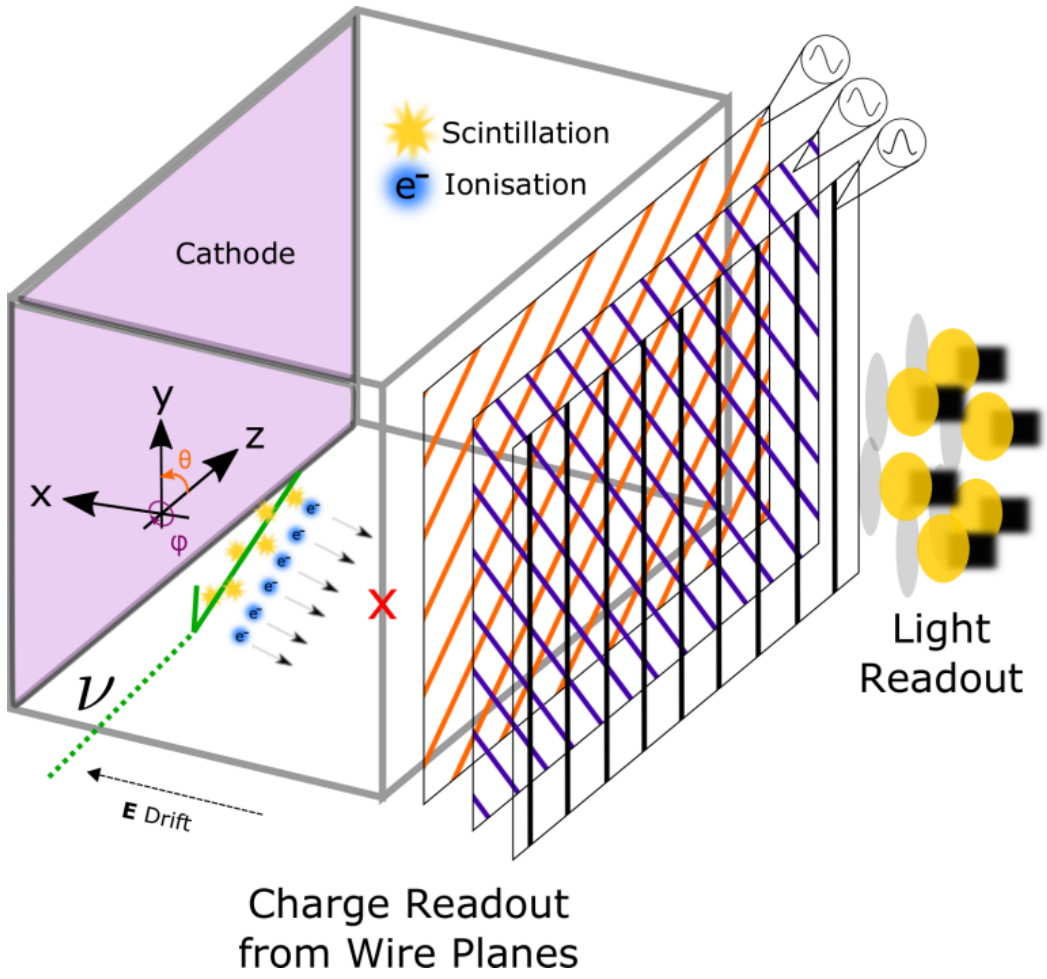
New HNL and HPS results from MicroBooNE

Other MicroBooNE BSM searches

The MicroBooNE experiment

- Liquid argon time projection chamber (LArTPC)
- Active volume 85 tonnes of liquid argon
- $2.6 \times 2.3 \times 10.4$ m^3
- Largest dataset of neutrino interactions in liquid argon (2015-2020)
- 175 collaborators from 37 institutions in 5 countries

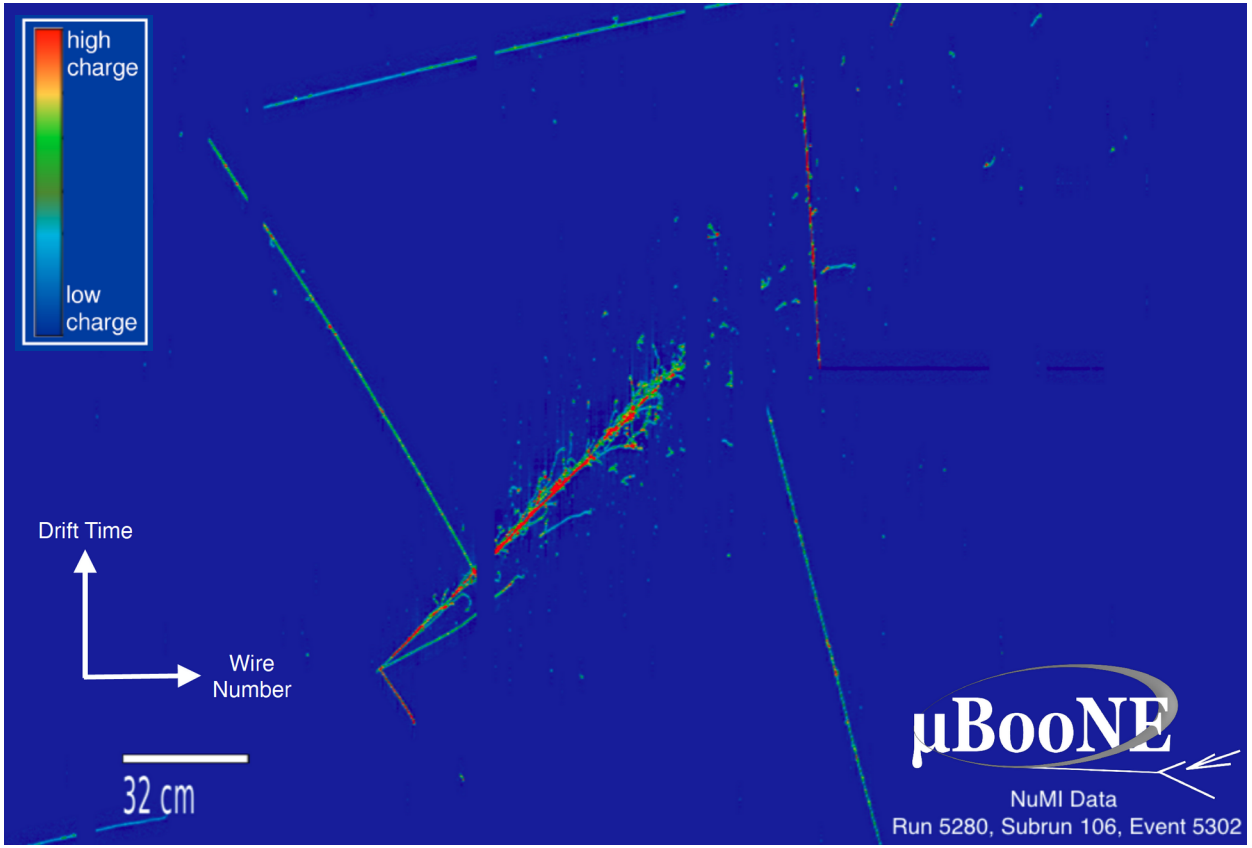
MicroBooNE LArTPC technology



- Scintillation and ionization signals used to produce bubble-chamber like images of events
- 3 planes of wires with 3mm pitch
- Array of 32 PMTs for light readout
- Excellent mm-scale spatial resolution
- Excellent calorimetry and low-energy reconstruction thresholds

LArTPC – event display

- Powerful particle identification
- Separation between electrons and gammas
- Can reconstruct full 3D image from the wire planes (and scintillation flash)
- Color is linked to deposited charge → calorimetry



Phys. Rev. D 103, 052002

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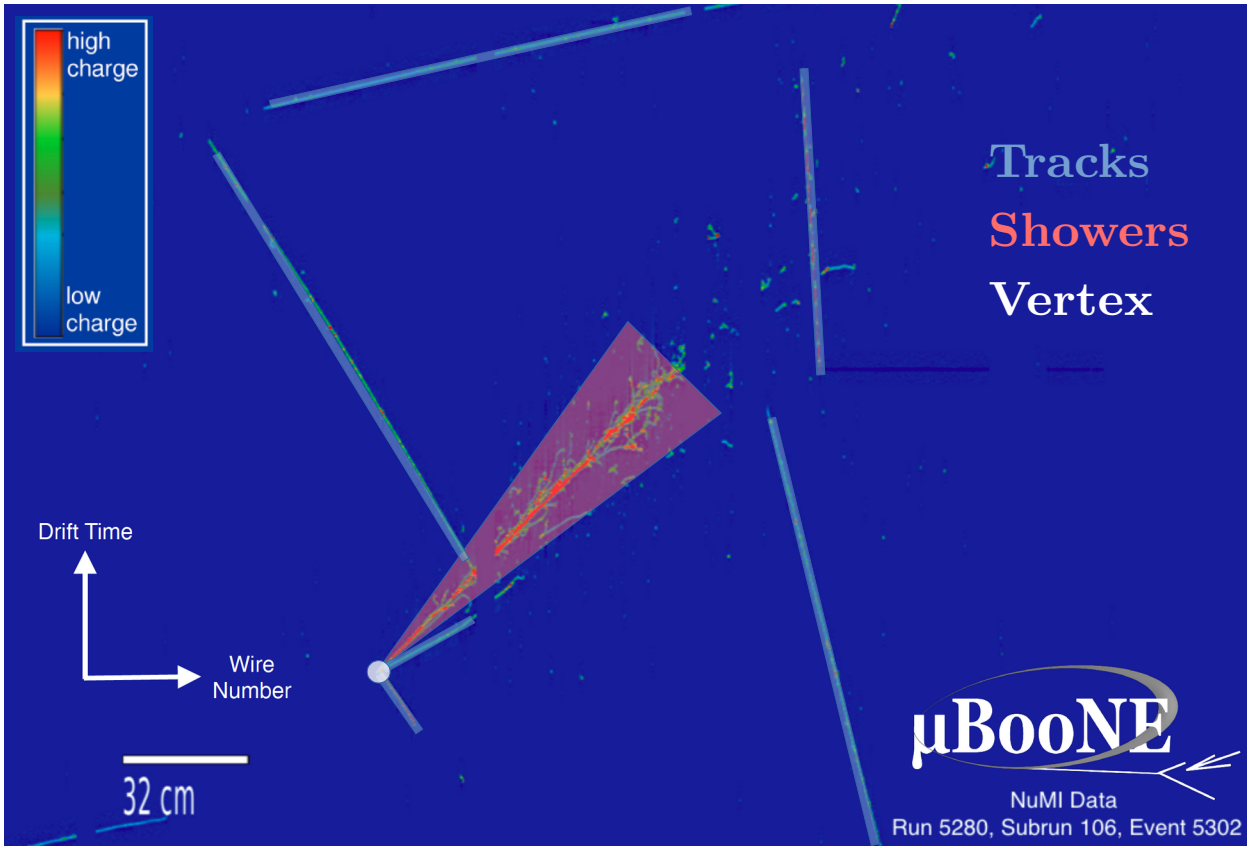

Phys. Rev. D 103, 052002

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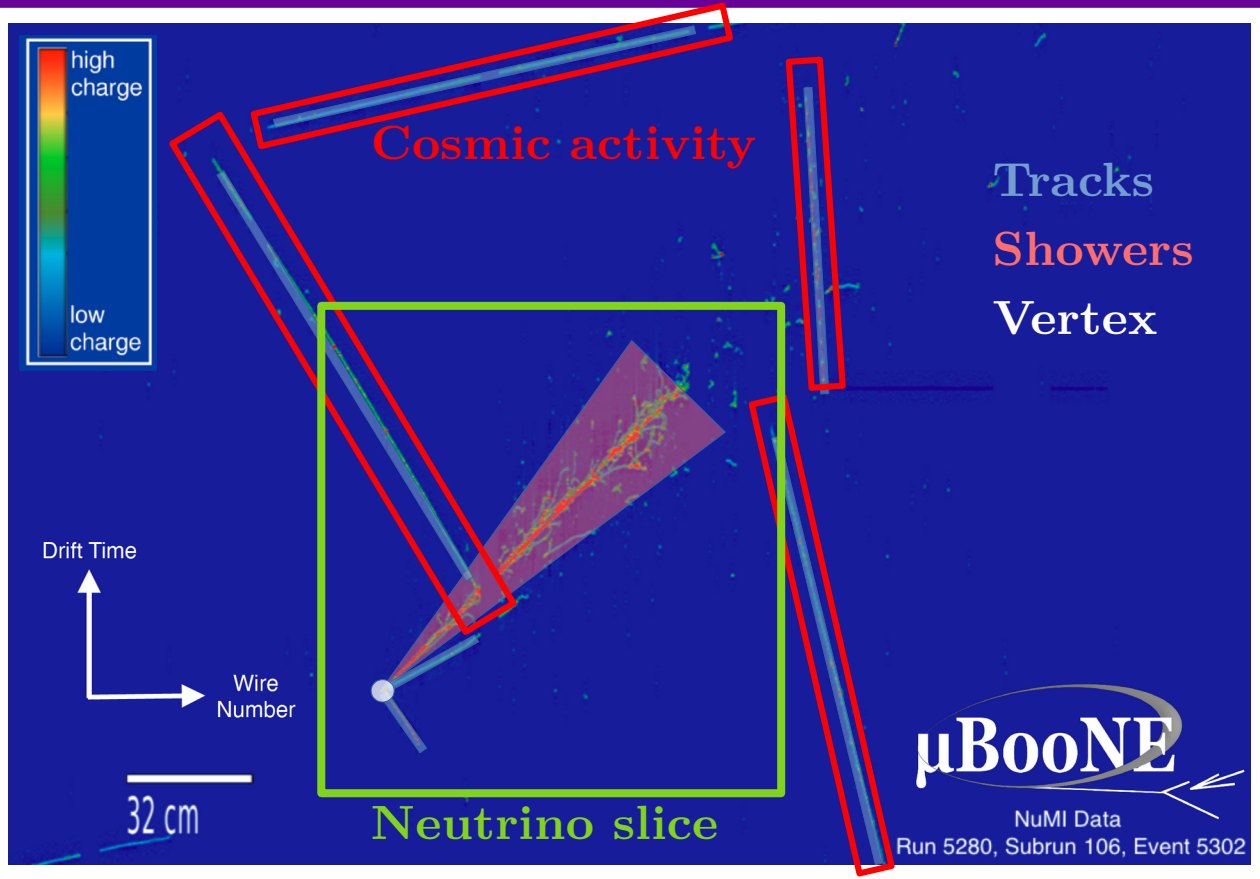
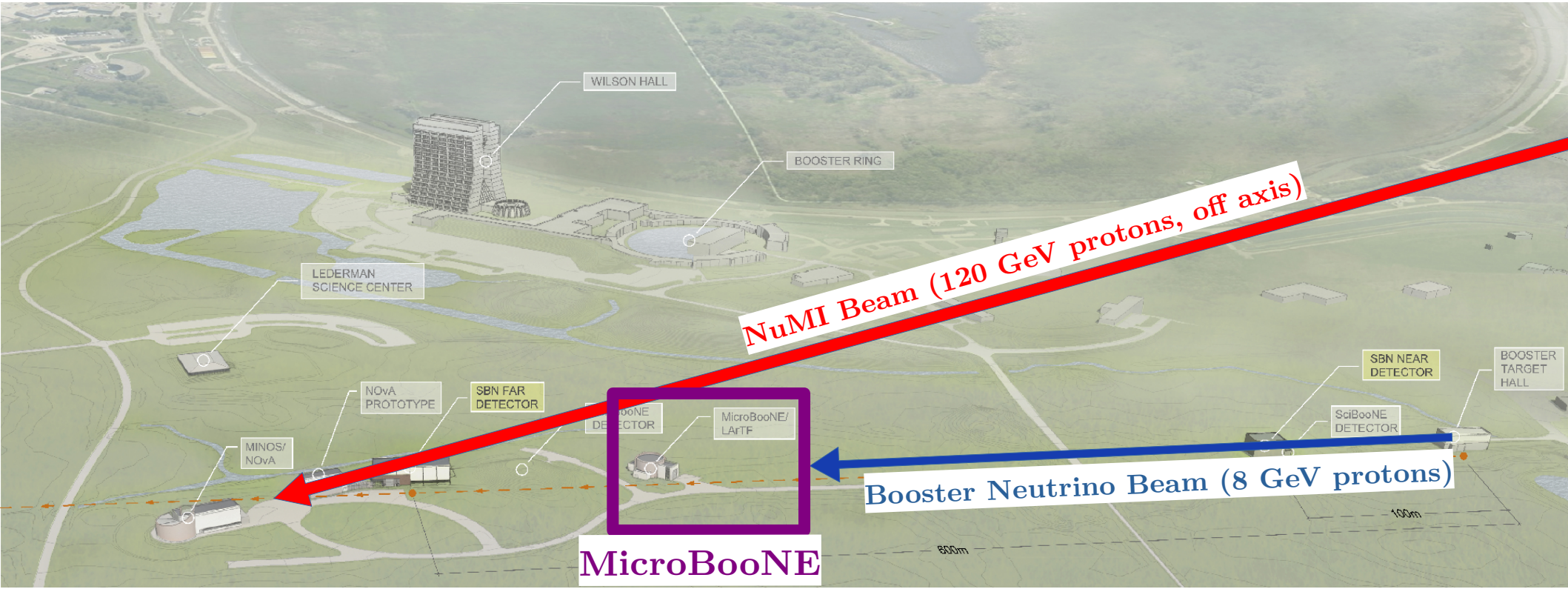


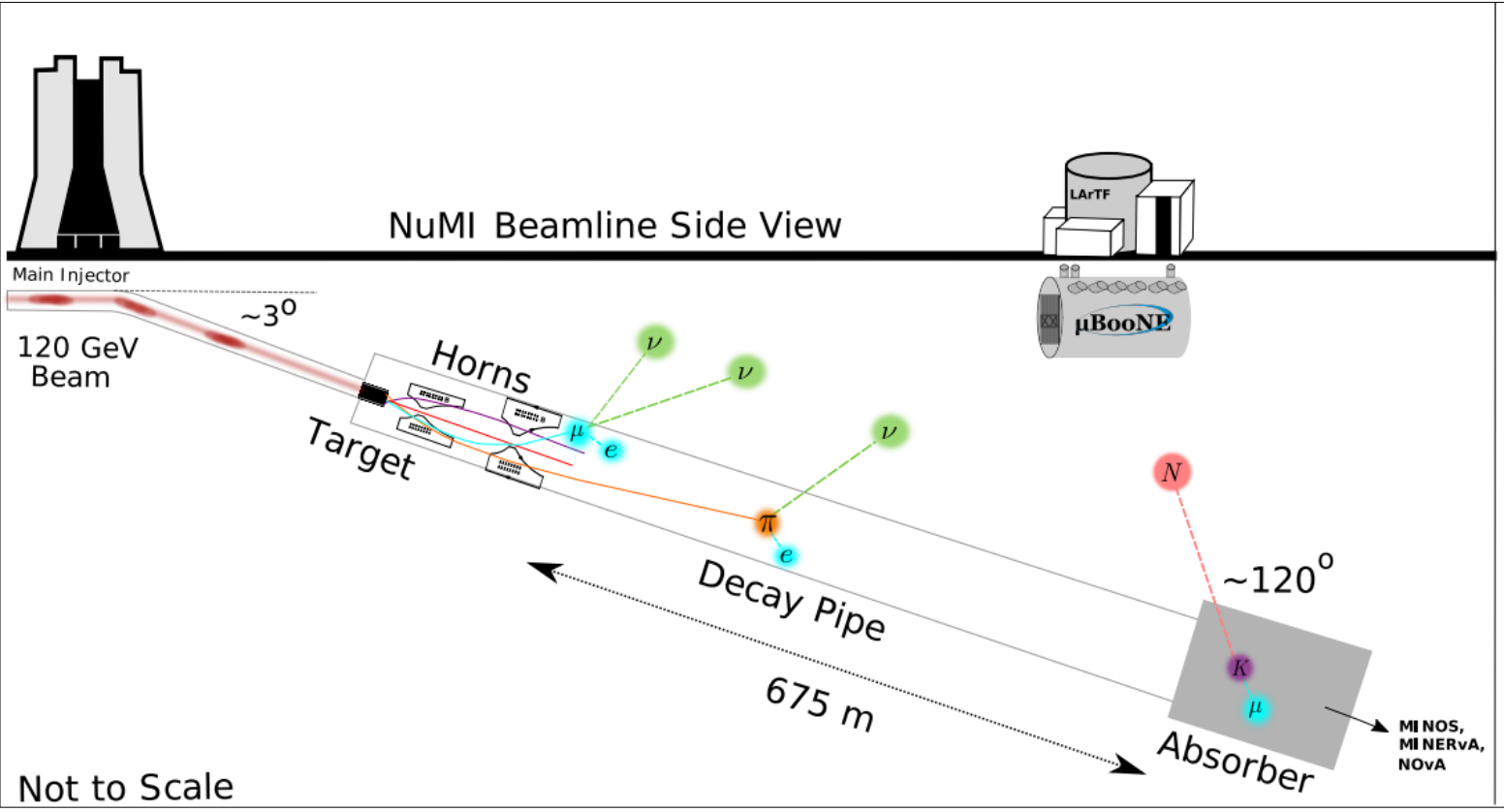
Phys. Rev. D 103, 052002

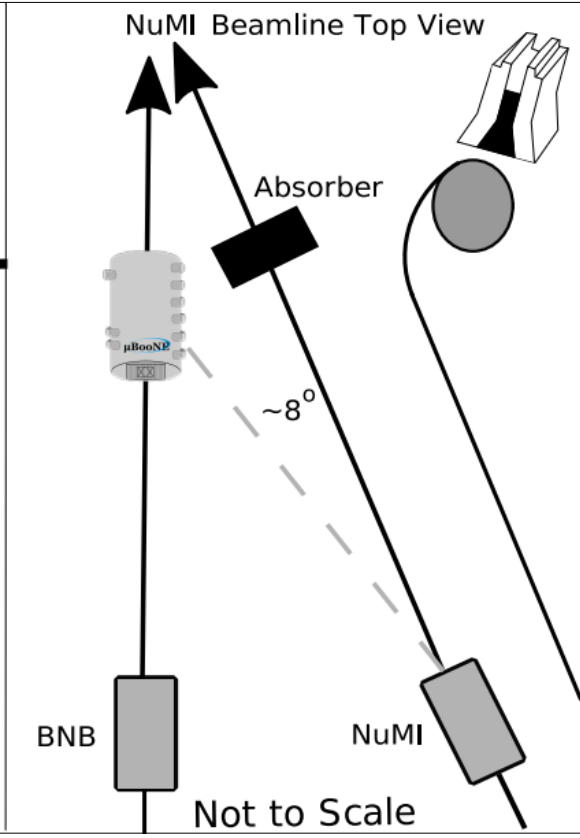
BNB and NuMI neutrino beams

Aerial view of Fermilab, Batavia, Illinois, USA



Neutrinos from the Main Injector (NuMI) neutrino beam

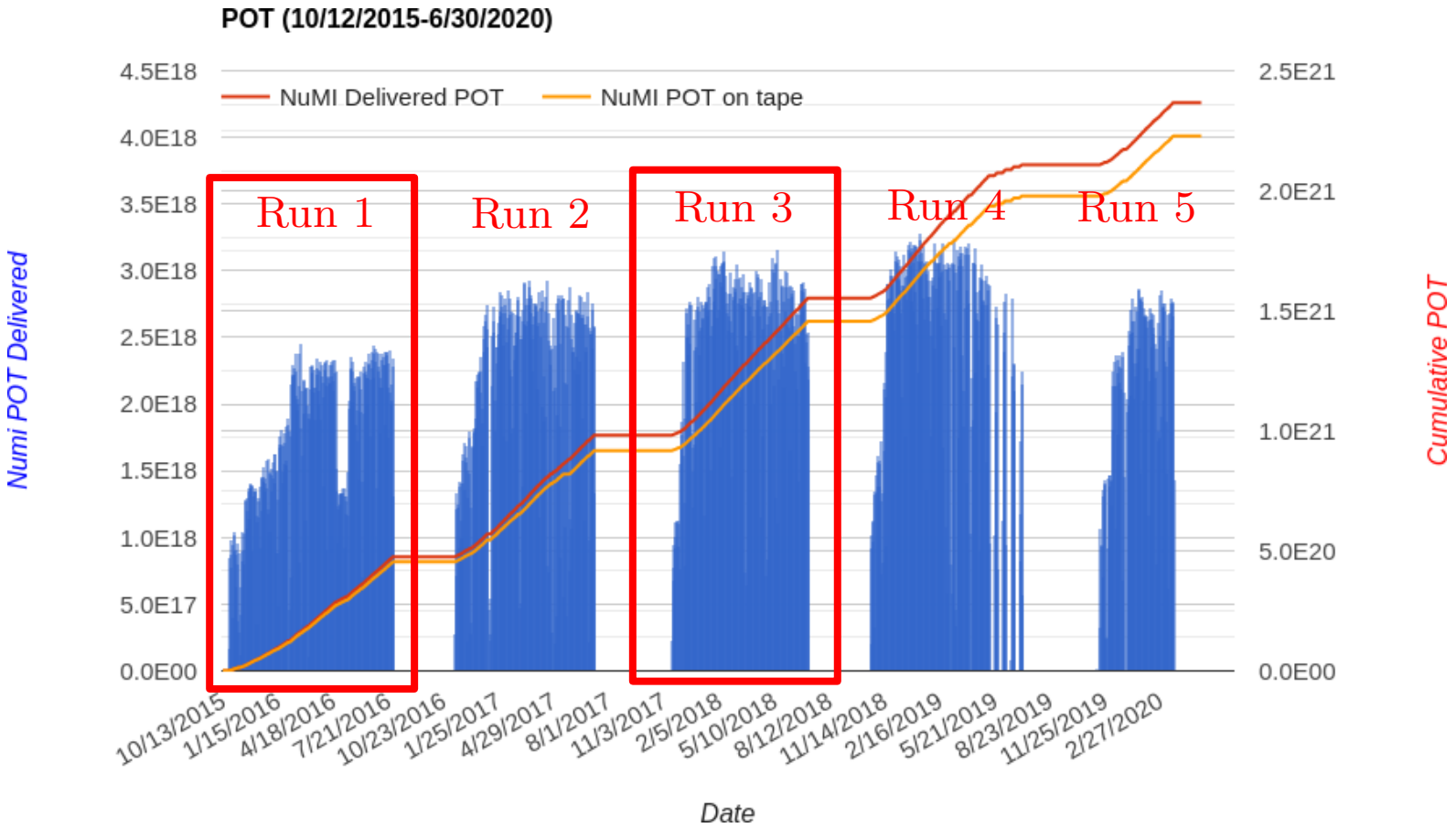




13% of beam protons don't interact with the target.

They can produce kaons at the absorber (~100 m from MicroBooNE).

MicroBooNE data



New HNL and HPS results use NuMI runs 1 and 3 data (~50% of dataset)

Overview

The MicroBooNE experiment

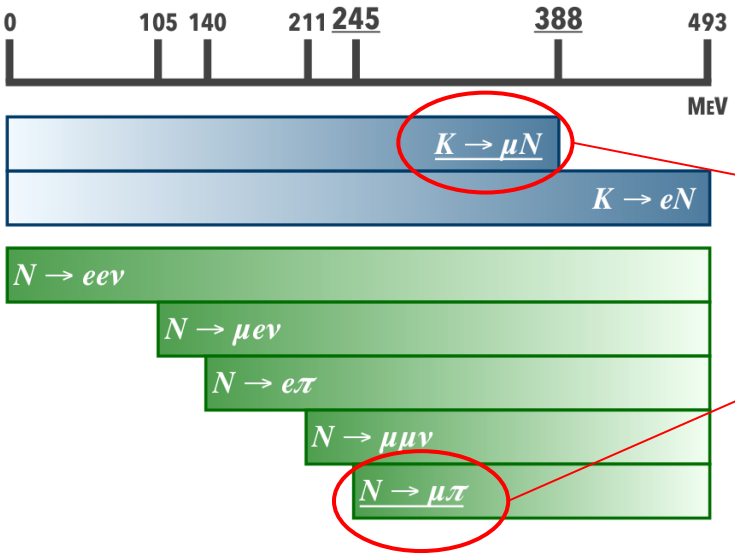
Heavy Neutral Leptons and Higgs Portal Scalars

New HNL and HPS results from MicroBooNE

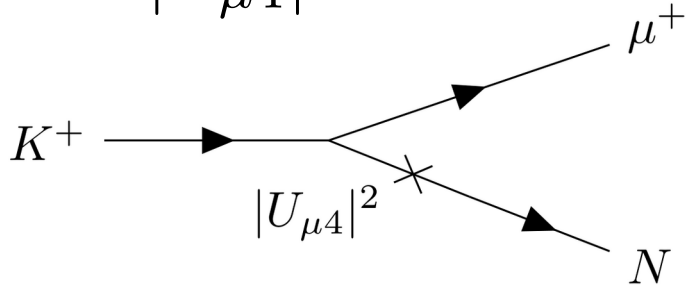
Other MicroBooNE BSM searches

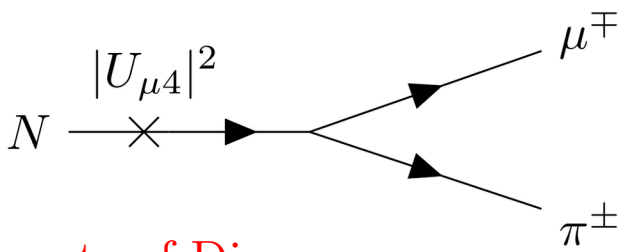
Heavy Neutral Leptons (HNL)

- Extension of the PMNS matrix $|U_{\alpha 4}|^2 \, (\alpha = e, \mu, \tau)$
- Flavor eigenstates $\nu_\alpha = \sum_i U_{\alpha_i} \nu_i + U_{\alpha 4} N$
- We set $|U_{e4}|^2 = |U_{\tau 4}|^2 = 0$ and place limits on $|U_{\mu 4}|^2$



Focused on these production and decay channels

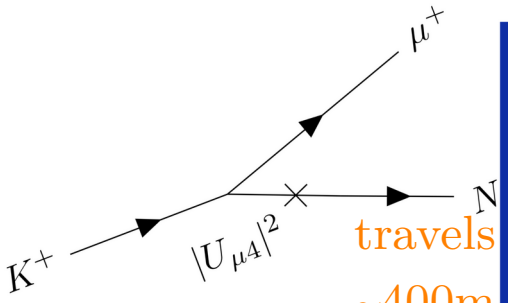


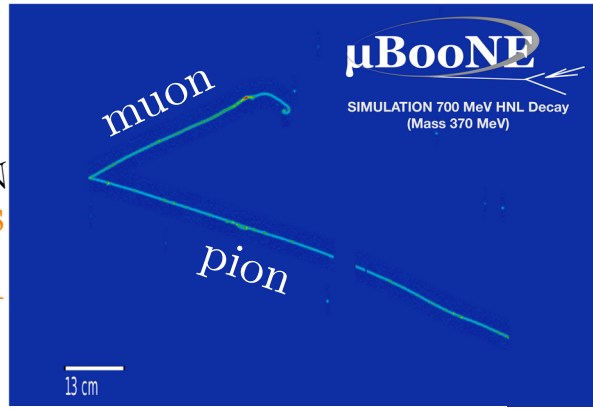


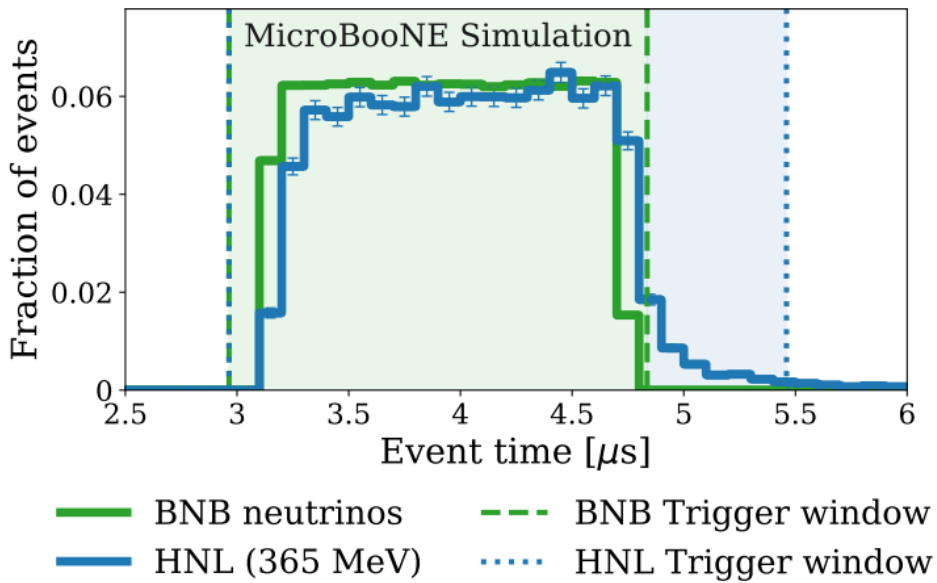
Majorana HNL double the rate of Dirac

MicroBooNE first HNL search (2020)

- Phys. Rev D 101, 052001
- First search of HNLs in LArTPCs
- Produced at **BNB target**, using 2.0×10^{20} POT
- Novel "late trigger" window
  - HNLs take longer than neutrinos to travel → effectively removed neutrino background
- Set limits for 260-385 MeV

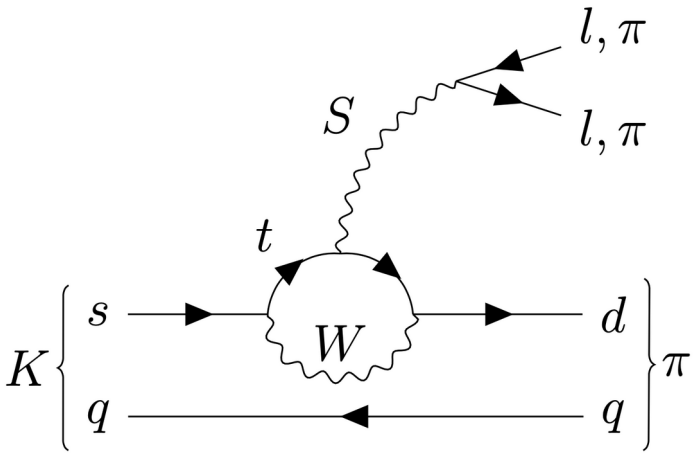






Higgs Portal Scalars (HPS)

- Portal between SM and dark sector via the Higgs
- Neutral real singlet scalar boson mixes with Higgs boson with mixing angle θ
- Dark scalar acquires coupling to SM fermions proportional to $\sin(\theta) \rightarrow \theta$



We will focus on Kaon decay at rest in the NuMI absorber

$m_k - m_\pi \simeq 354$ MeV $\rightarrow$ decays to $e^+e^-, \mu^+\mu^-, \pi^0\pi^0, \pi^+\pi^-$

PHYSICAL REVIEW D **100,** 115039 (2019)

Probing the Higgs portal at the Fermilab short-baseline neutrino experiments

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(Received 11 October 2019; published 23 December 2019)

The Fermilab short-baseline neutrino (SBN) experiments, MicroBooNE, ICARUS, and SBND, are expected to have significant sensitivity to light weakly coupled hidden sector particles. Here we study the capability of the SBN experiments to probe dark scalars interacting through the Higgs portal. We investigate production of dark scalars using both the Fermilab booster 8 GeV and NuMI 120 GeV proton beams, simulating kaons decaying to dark scalars and taking into account the beam line geometry. We also investigate strategies to mitigate backgrounds from beam-related neutrino scattering events. We find that SBND, with its comparatively short $\mathcal{O}(100\ \mathrm{m})$ baseline, will have the best sensitivity to scalars produced from the booster, while ICARUS, with its large detector volume, will provide the best limits on off-axis dark scalar production from NuMI. The SBN experiments can provide leading tests of dark scalars with masses in the 50–350 MeV range in the near term. Our results motivate dedicated experimental searches for dark scalars and other long-lived hidden sector states at these experiments.

DOI: 10.1103/PhysRevD.100.115039

I. INTRODUCTION

Light weakly coupled hidden sectors may play a role in addressing some of the outstanding puzzles in particle physics and cosmology, such as dark matter, neutrino masses, the matter-antimatter asymmetry, the hierarchy problem, and inflation [1–4]. They also provide an interesting physics target for a variety of intensity frontier experiments. One well-known example is proton beam fixed target experiments, including those used to study neutrino oscillations. In these experiments, a beam of relativistic hidden sector particles produced in the primary proton-target collisions passes through a downstream detector and decays to visible Standard Model (SM) particles, providing a distinctive signature that can be discriminated from beam-related neutrino and cosmic-ray induced backgrounds.

The short-baseline neutrino (SBN) program at Fermilab utilizes three liquid argon time projection chamber detectors—short-baseline near detector (SBND) [5], MicroBooNE [6], and ICARUS [7]—situated along the Booster Neutrino Beam (BNB) [8]. While the primary physics goals of the SBN program include searches for eV-scale sterile neutrinos (motivated by the LSND [9] and MiniBooNE [10–12] anomalies) and measurements of neutrino-nucleus scattering cross sections, these experiments are also expected to have significant sensitivity to hidden sector particles in the MeV–GeV range. In this paper we study the capability of the SBN experiments to search for dark scalar particles S interacting via the Higgs portal.

We consider production of dark scalars from collisions of both the 8 GeV booster and the 120 GeV main injector protons. Concerning the latter, MicroBooNE and ICARUS are located approximately 8° and 6° off axis with respect to the Neutrinos at the Main Injector (NuMI) beam, implying that the associated flux of dark scalars passing through these detectors can be substantial. We perform a careful simulation of the BNB and NuMI beam lines that includes the targets, magnetic focusing horns, and absorbers. While we also attempt to take account of various experimental factors such as particle identification and reconstruction efficiencies, detection thresholds, and measurement resolutions, a complete characterization of these parameters is still under active experimental study, so our assumptions in this regard must be considered preliminary. We consider two primary dark scalar signal channels in detail: (i) the $S \rightarrow e^+e^-$ channel, relevant for scalars below the dimuon threshold, and (ii) the combined $S \rightarrow \mu^+\mu^-, \pi^+\pi^-$ channels, which are important for somewhat heavier scalars.

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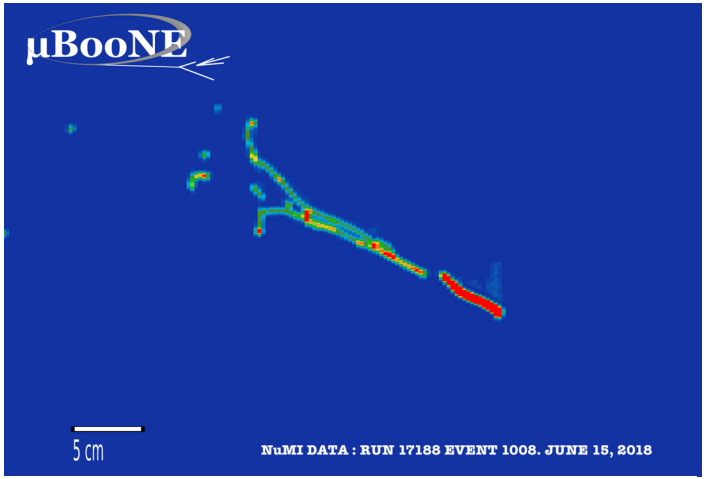
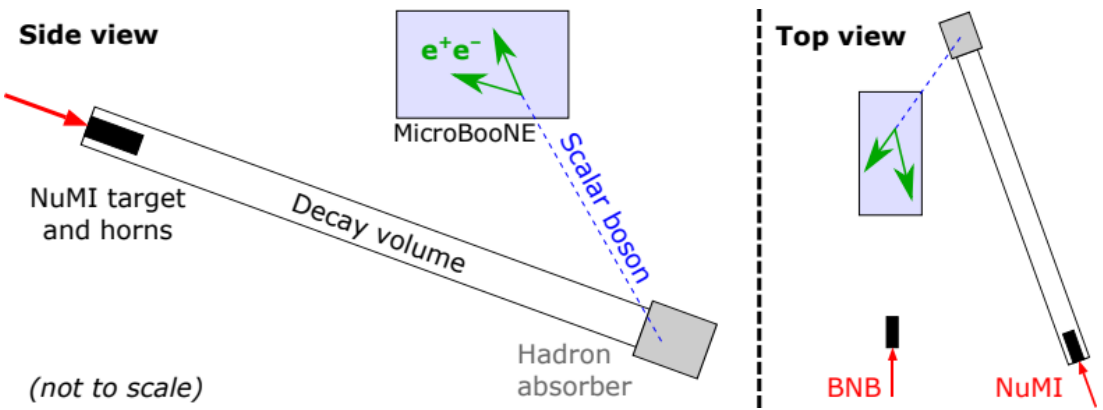
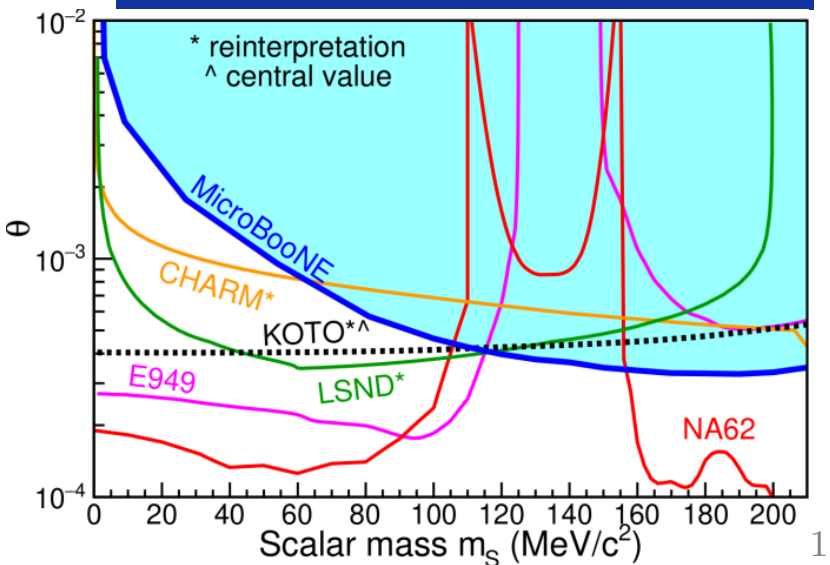
Phys. Rev. D 100, 115039

MicroBooNE previous HPS search (2021)

- Phys. Rev. Lett. 127, 151803
- Produced at **NuMI absorber**, decays to e^+e^-
- First BSM e^+e^- search of any LArTPC
- One candidate event, consistent with background expectation







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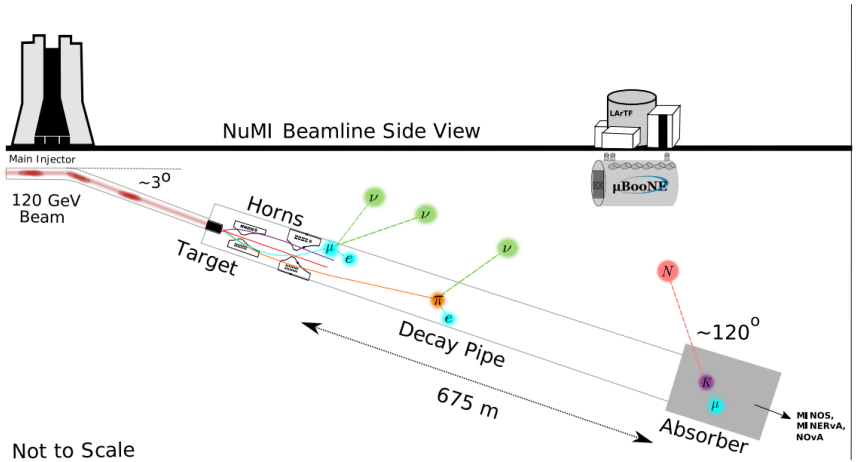
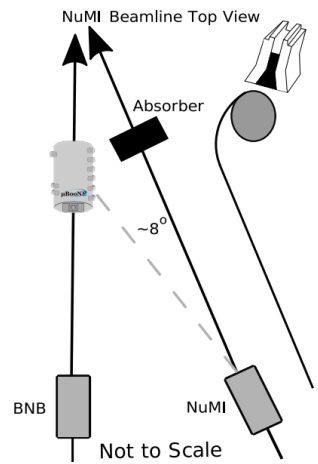
Other MicroBooNE BSM searches

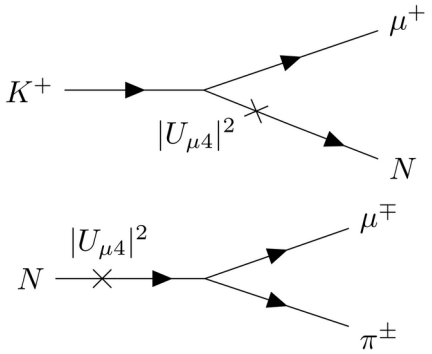
Latest HNL + HPS search (2022)

Searches for HNL and HPS from KDAR from NuMI absorber

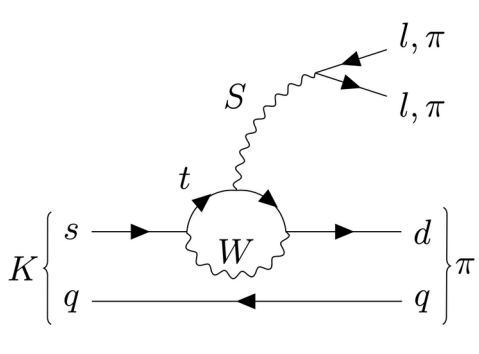
- HNL: BNB target (2020) → NuMI absorber (2022)
- Monoenergetic, isotropic LLP in K rest frame $E_{\mathrm{LLP}} = \dfrac{m_K^2 + m_{\mathrm{LLP}}^2 - m_{\mu,\pi}^2}{2m_K}$







$N \to \mu^\pm \pi^\mp$

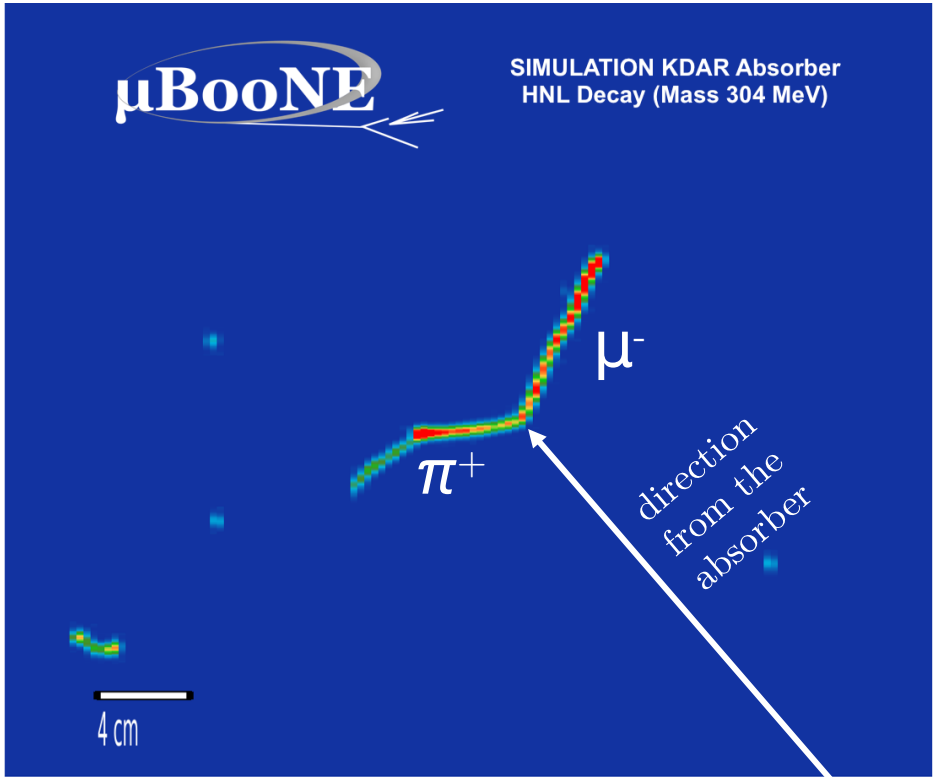


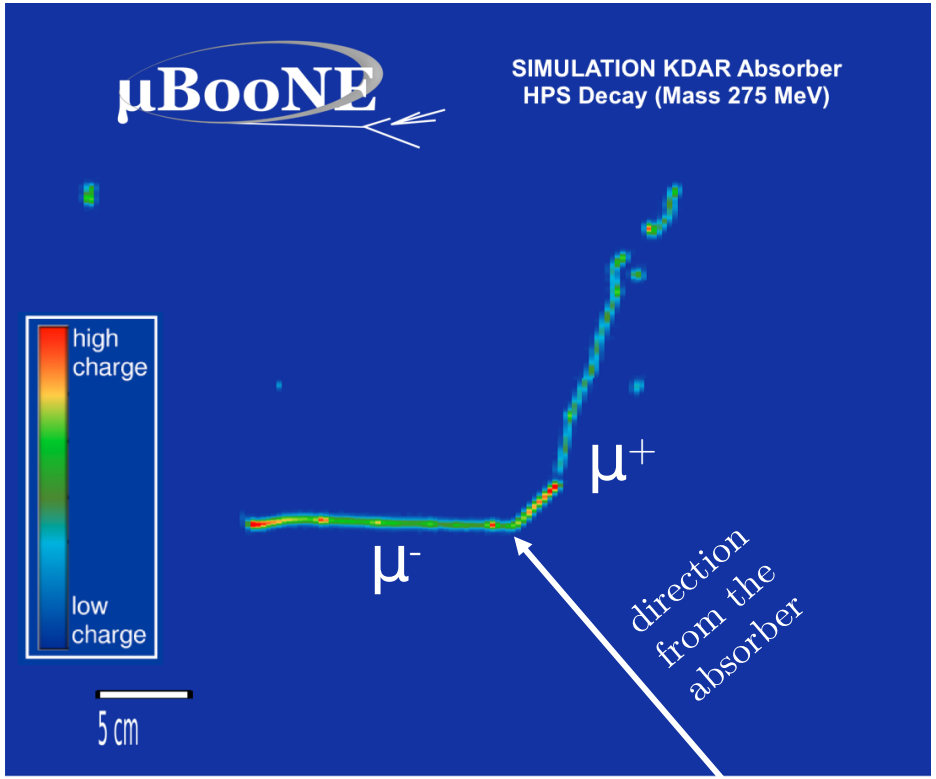
$S \to \mu^+ \mu^-$

arXiv:2207.03840

Latest HNL + HPS search (2022)

Similar two-track topology → similar selection strategy





HNL decay channel same as previous search.

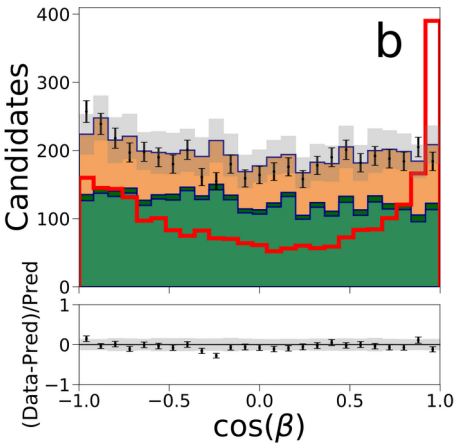
HPS: e^+e^- (2021) → $\mu^+\mu^-$ (2022)

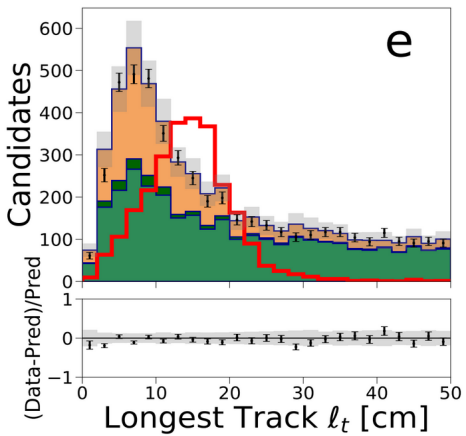
arXiv:2207.03840

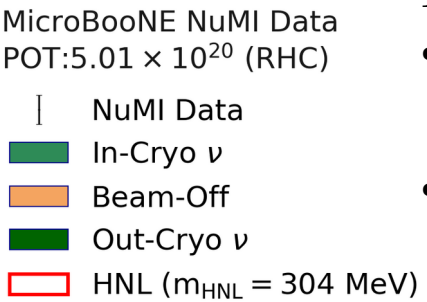
Search strategy

- Simulate signal
  - HNL: 12 mass points $246 \leq m_{\mathrm{HNL}} \leq 385$ MeV
  - HPS: 8 mass points $212 \leq m_{\mathrm{HPS}} \leq 279$ MeV
- After preselection, train separate BDTs for each sample using *xgboost*

A couple of selected background kinematics (for full set see next slide):







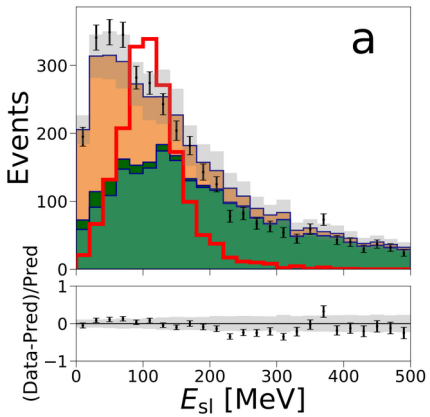
β = Angle w.r.t. absorber

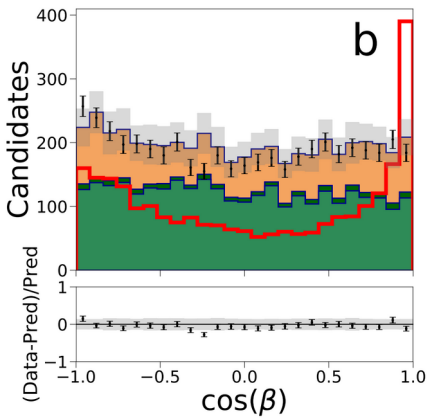
Backgrounds:

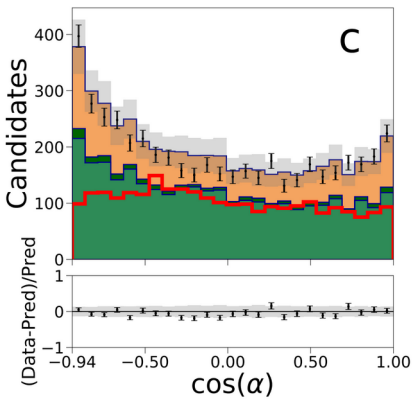
- Beam-off: detector triggered by cosmic ray
- In/Out-Cryo: neutrino interactions in/out of the detector

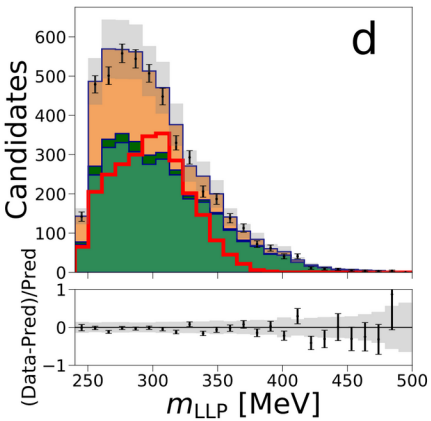
arXiv:2207.03840

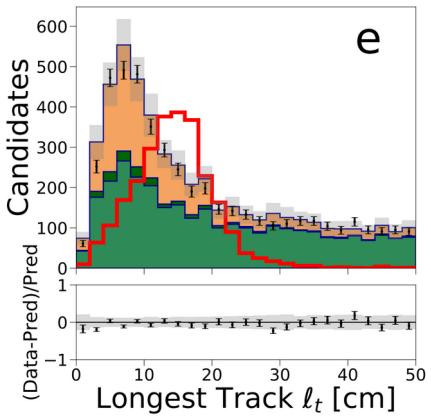
Full signal/background comparison

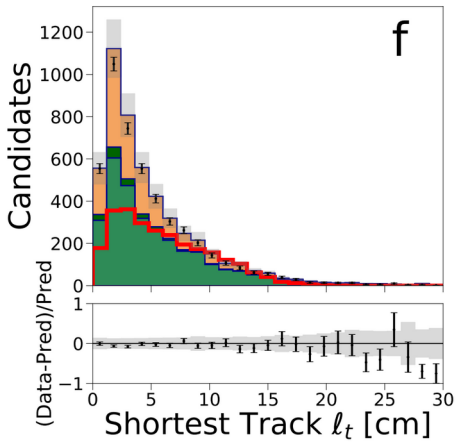


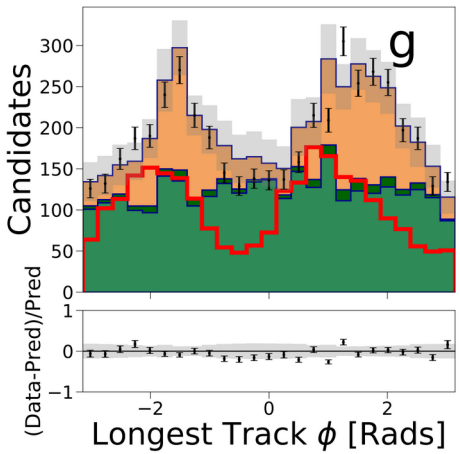










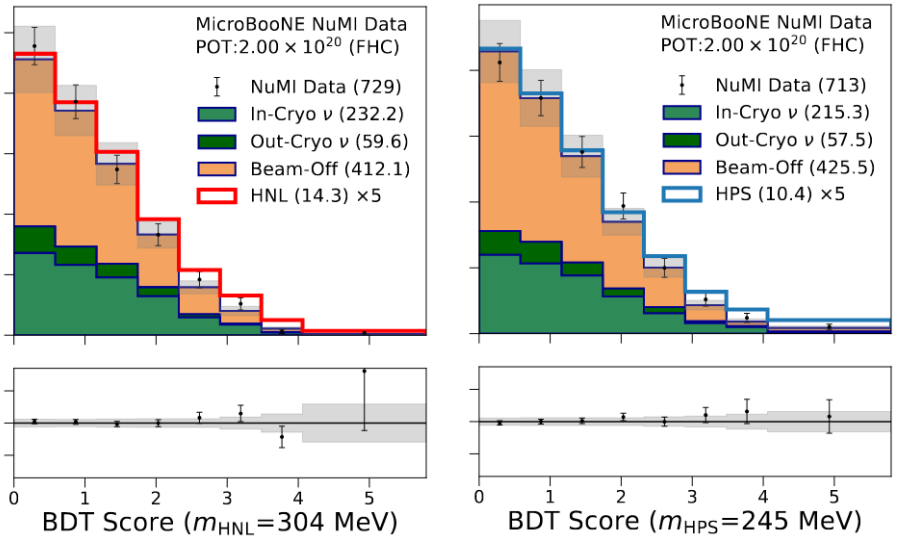


MicroBooNE NuMI Data
POT:5.01×10^{20} (RHC)

- NuMI Data
- In-Cryo ν
- Beam-Off
- Out-Cryo ν
- HNL ($m_{HNL} = 304$ MeV)

arXiv:2207.03840

Results

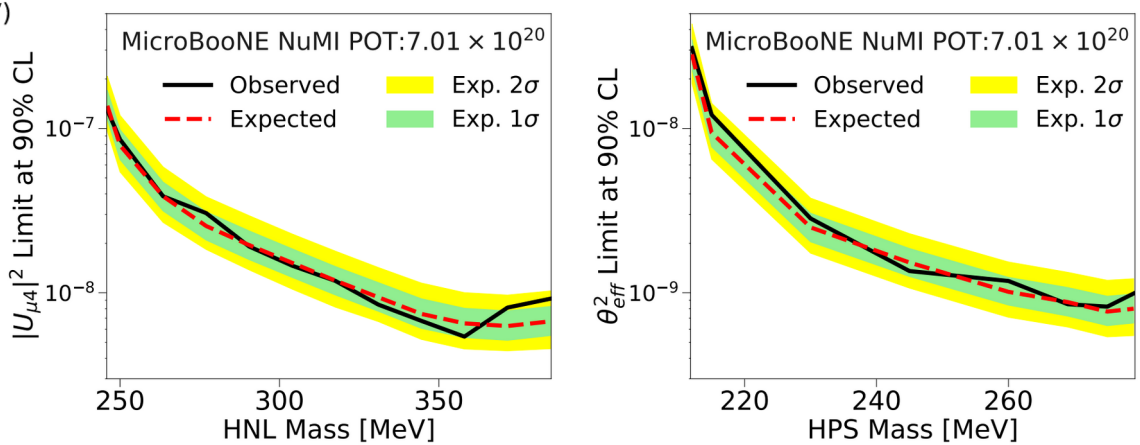


Trained BDT applied to data and simulation

← Comparison between data and sum of backgrounds for one mass (HNL, HPS)

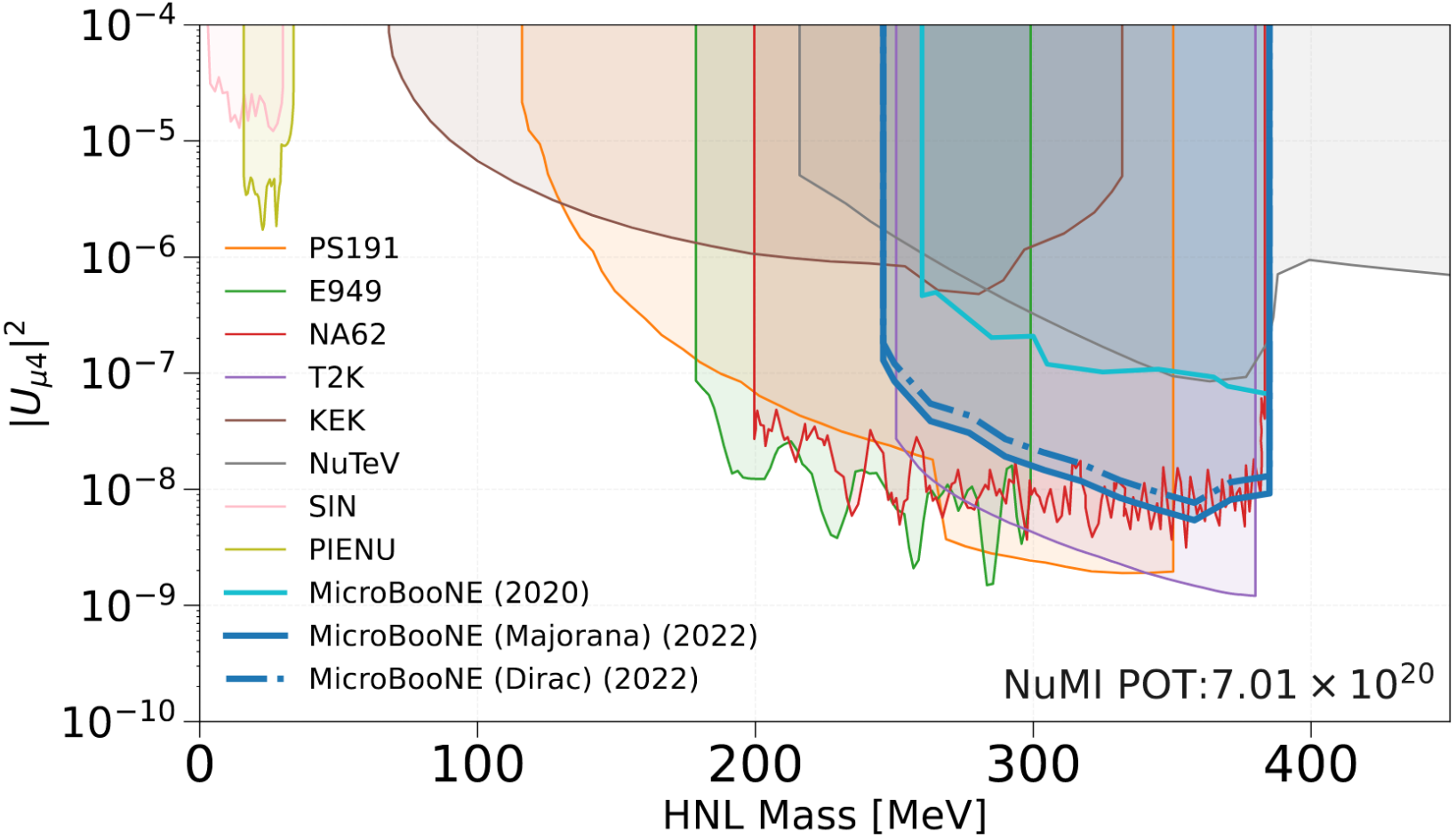
Background and data in good agreement

- Modified frequentist CLs method
- BDT score distribution + uncertainties as input



arXiv:2207.03840

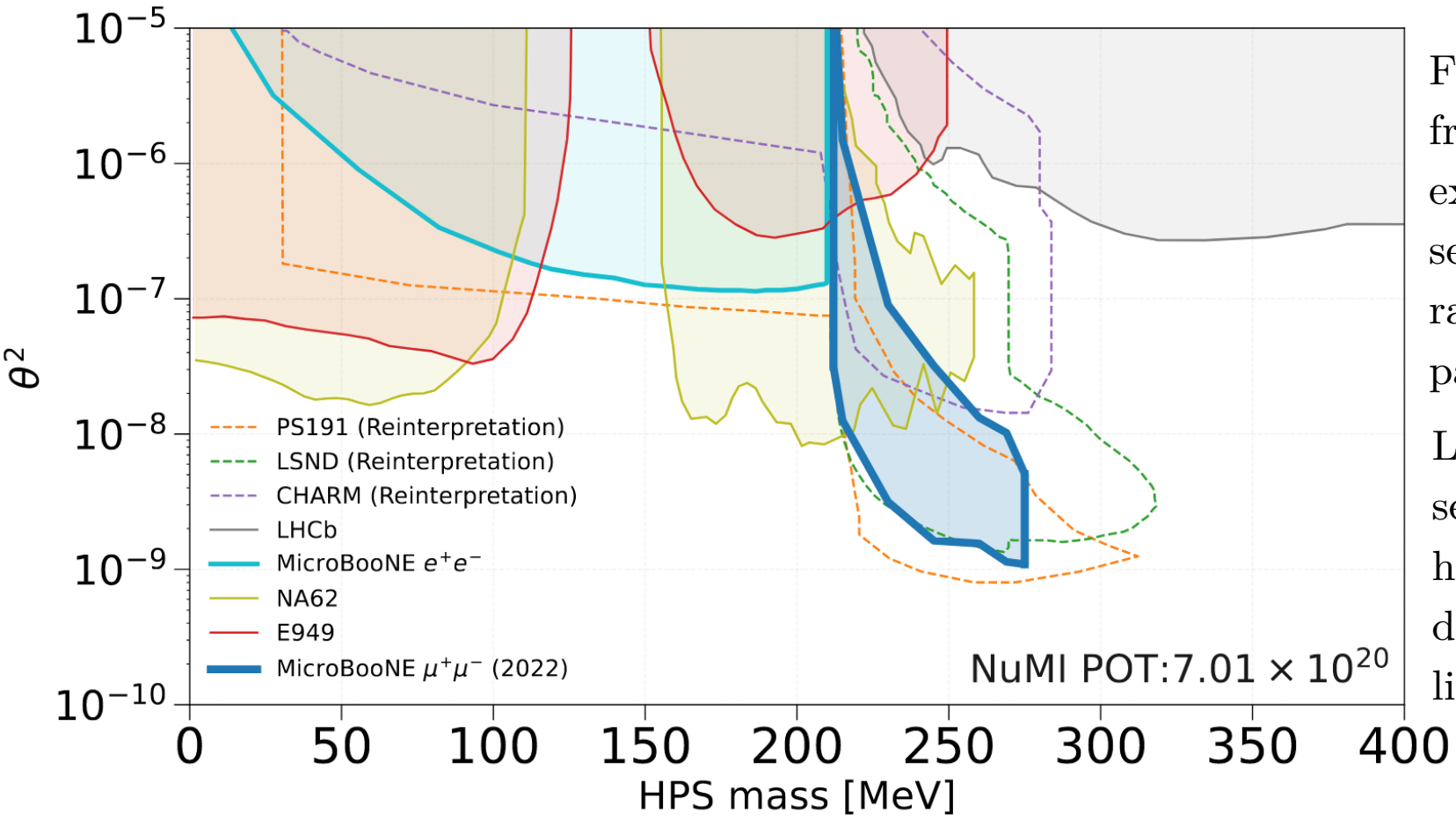
Latest MicroBooNE LLP results: HNLs



Order of magnitude improvement with respect to previous MicroBooNE result

arXiv:2207.03840

Latest MicroBooNE LLP results: HPS



First constraints from a dedicated experimental search in this range of parameters

Lack of sensitivity at high coupling due to short lifetime

arXiv:2207.03840

Overview

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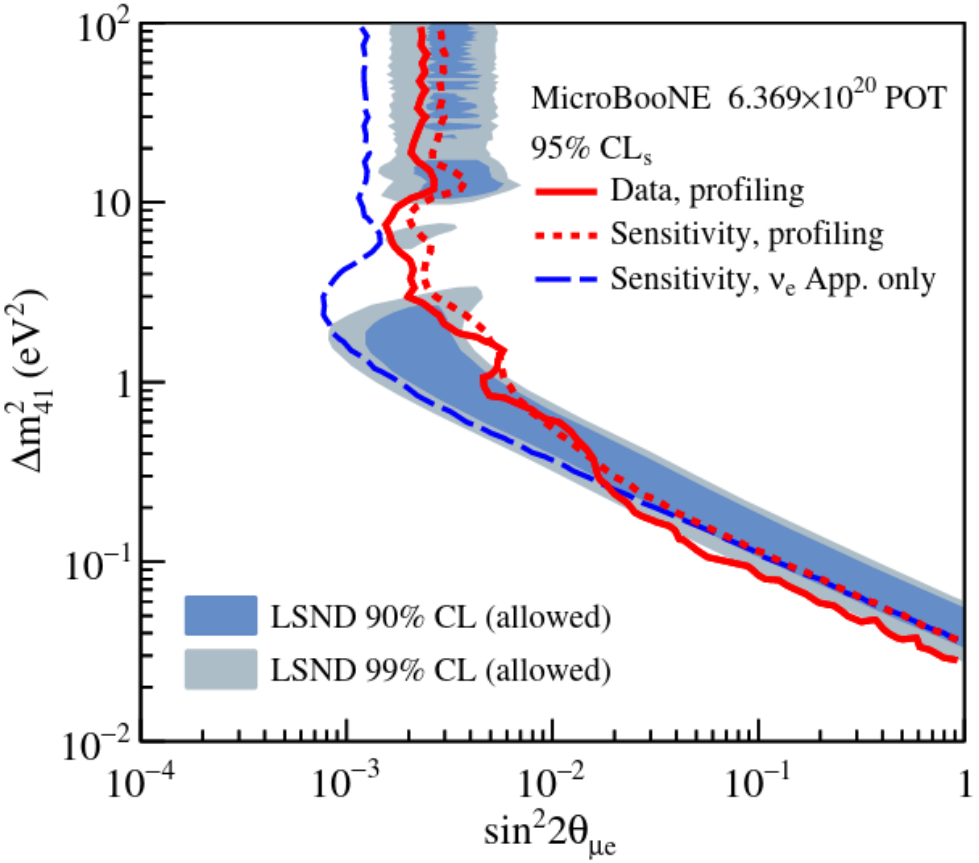
Heavy Neutral Leptons and Higgs Portal Scalars

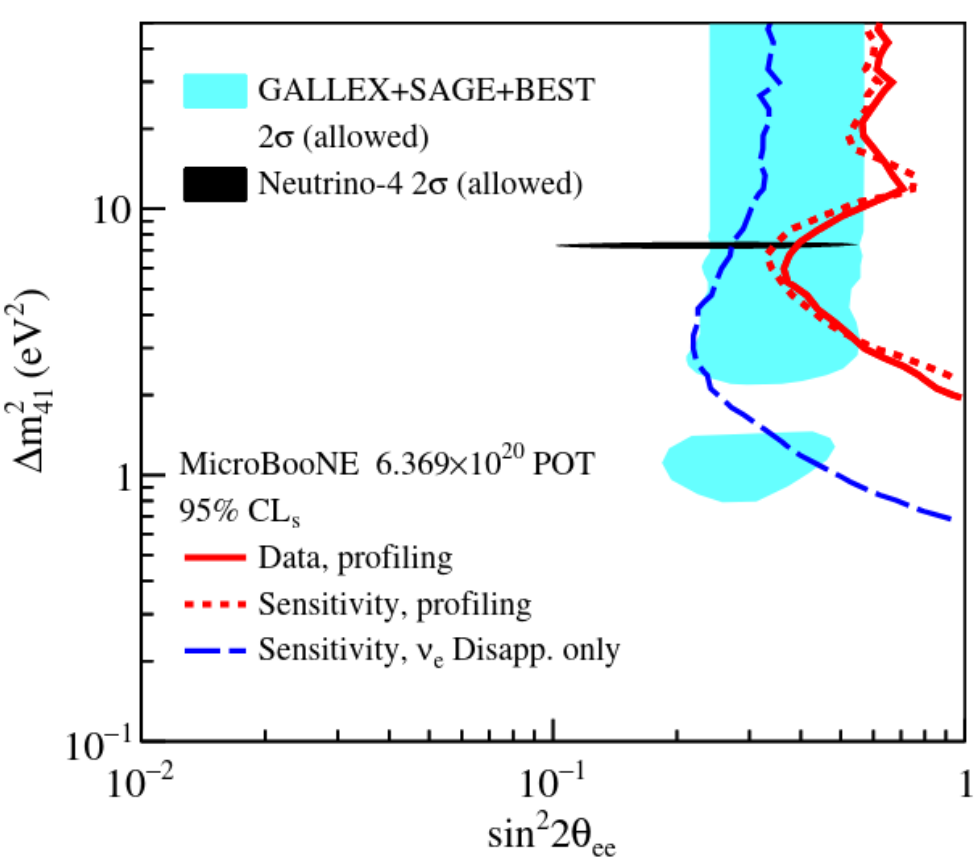
New HNL and HPS results from MicroBooNE

Other MicroBooNE BSM searches

3+1 light sterile search

- Uploaded on Oct 20: arXiv:2210.10216

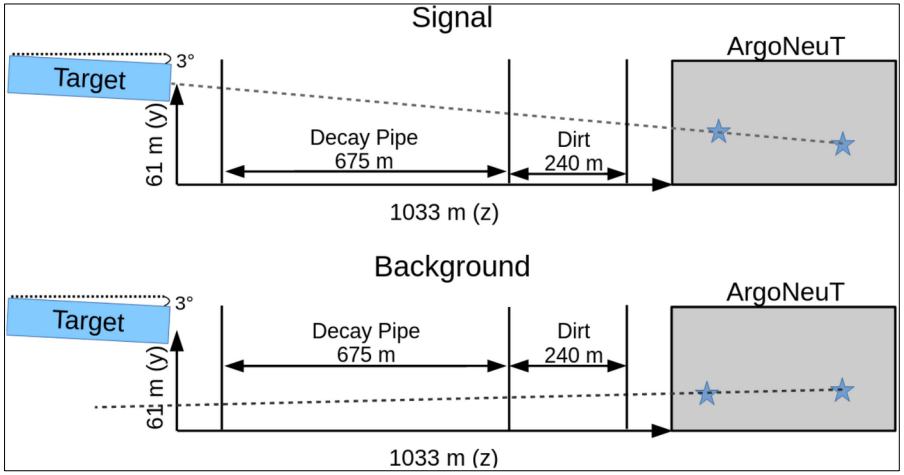




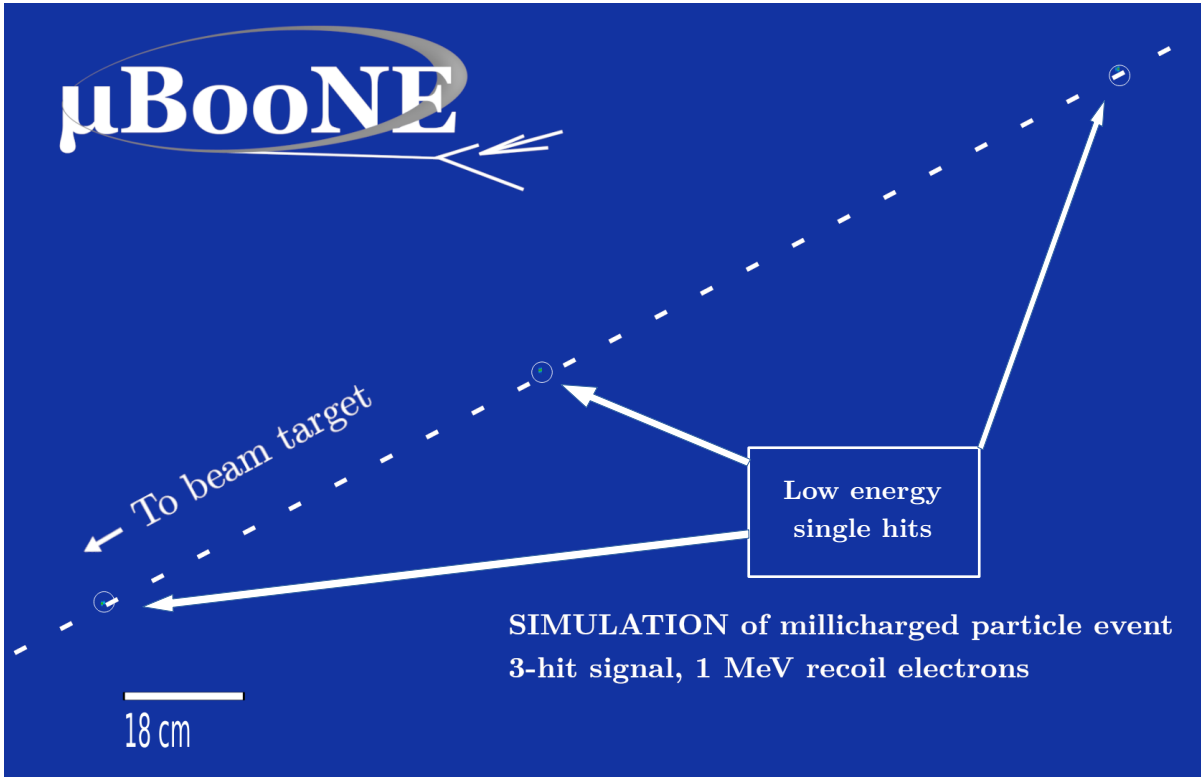
Other BSM: Millicharged particles (in progress)

Millicharged particles: feebly interacting LLPs with fractional charge

ArgoNeuT LArTPC performed such a search (on-axis with NuMI)



ArgoNeuT: [Phys. Rev. Lett. 124, 131801]

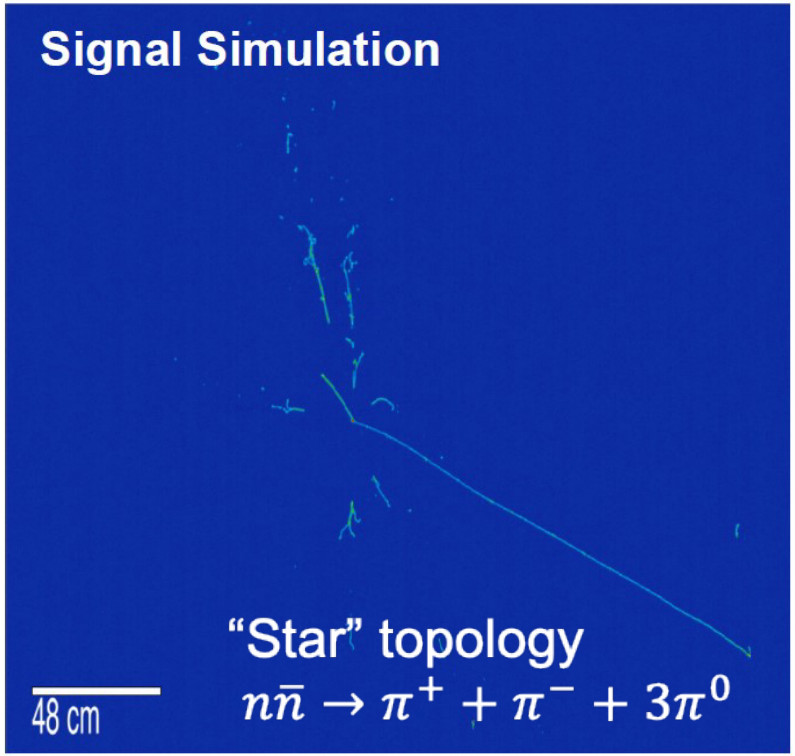


Isolated hits with argon electron in a straight line. Favors low-energy hits.

Other BSM (in progress)

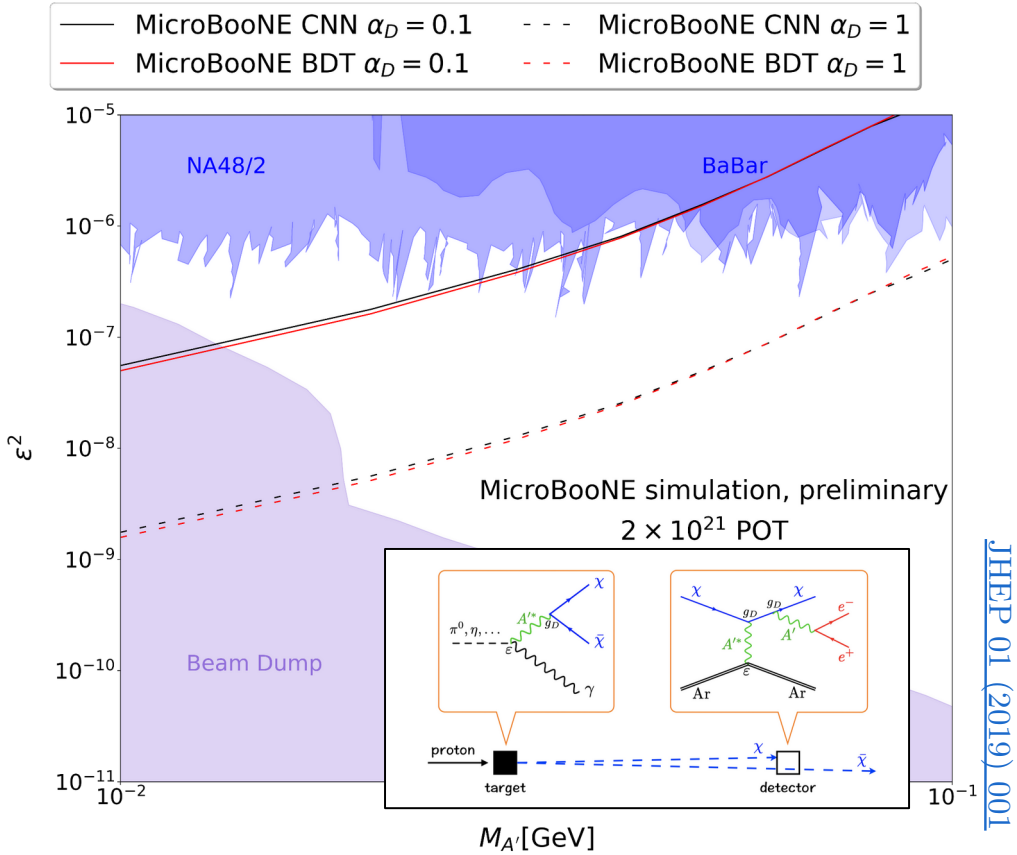
Neutron-antineutron oscillations

MICROBOONE-NOTE-1113-PUB



Dark tridents

MICROBOONE-NOTE-1118-PUB



More HNL and HPS decay channels as well. Stay tuned!

Summary

- Shown the latest published results for a search of HNL and HPS using the MicroBooNE LArTPC: arXiv:2207.03840
  - Expands upon previous results from 2020, 2021
  - LArTPCs capable of producing competitive results with complex signature topologies
- MicroBooNE has a rich BSM search program
  - 3+1 light sterile neutrino released two weeks ago: arXiv:2210.10216
  - Always something in the works!