Beyond the standard model particle searches in MicroBooNE

IOP Joint APP, HEPP and NP Annual Conference 2024

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on behalf of the MicroBooNE collaboration

Apr 10, 2024

Overview

The MicroBooNE experiment

Latest BSM search results

- Heavy Neutral Leptons (2024)
- Dark Tridents

Other MicroBooNE BSM searches

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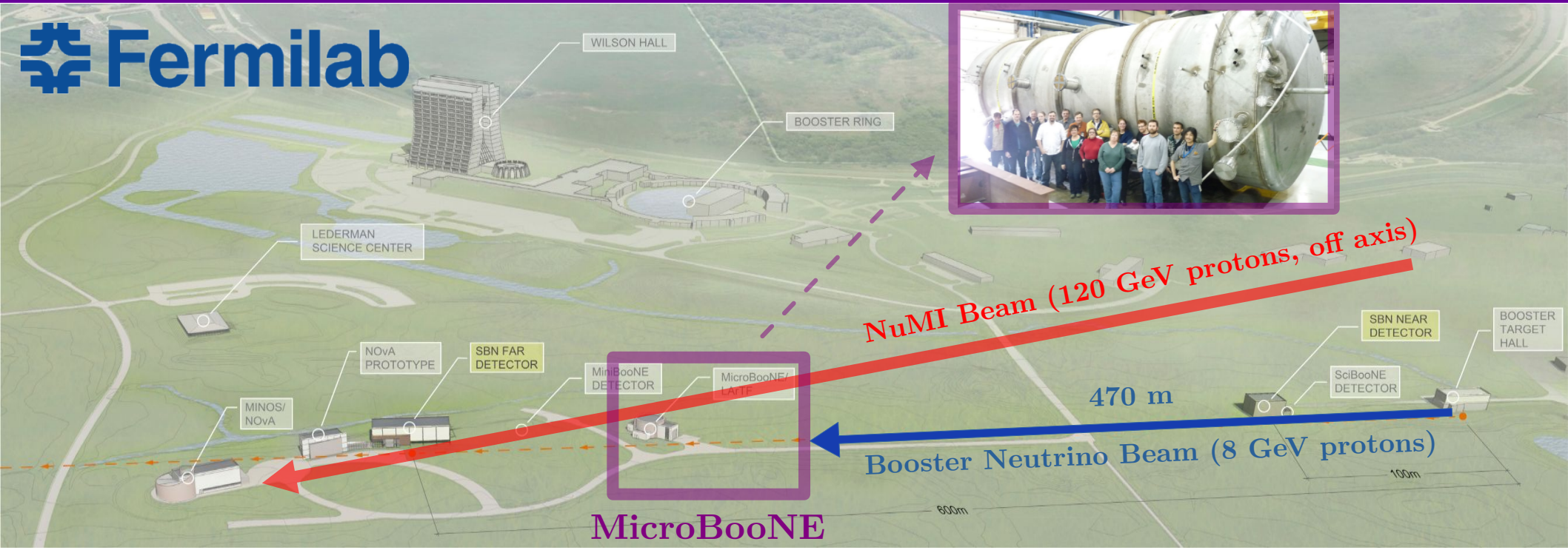
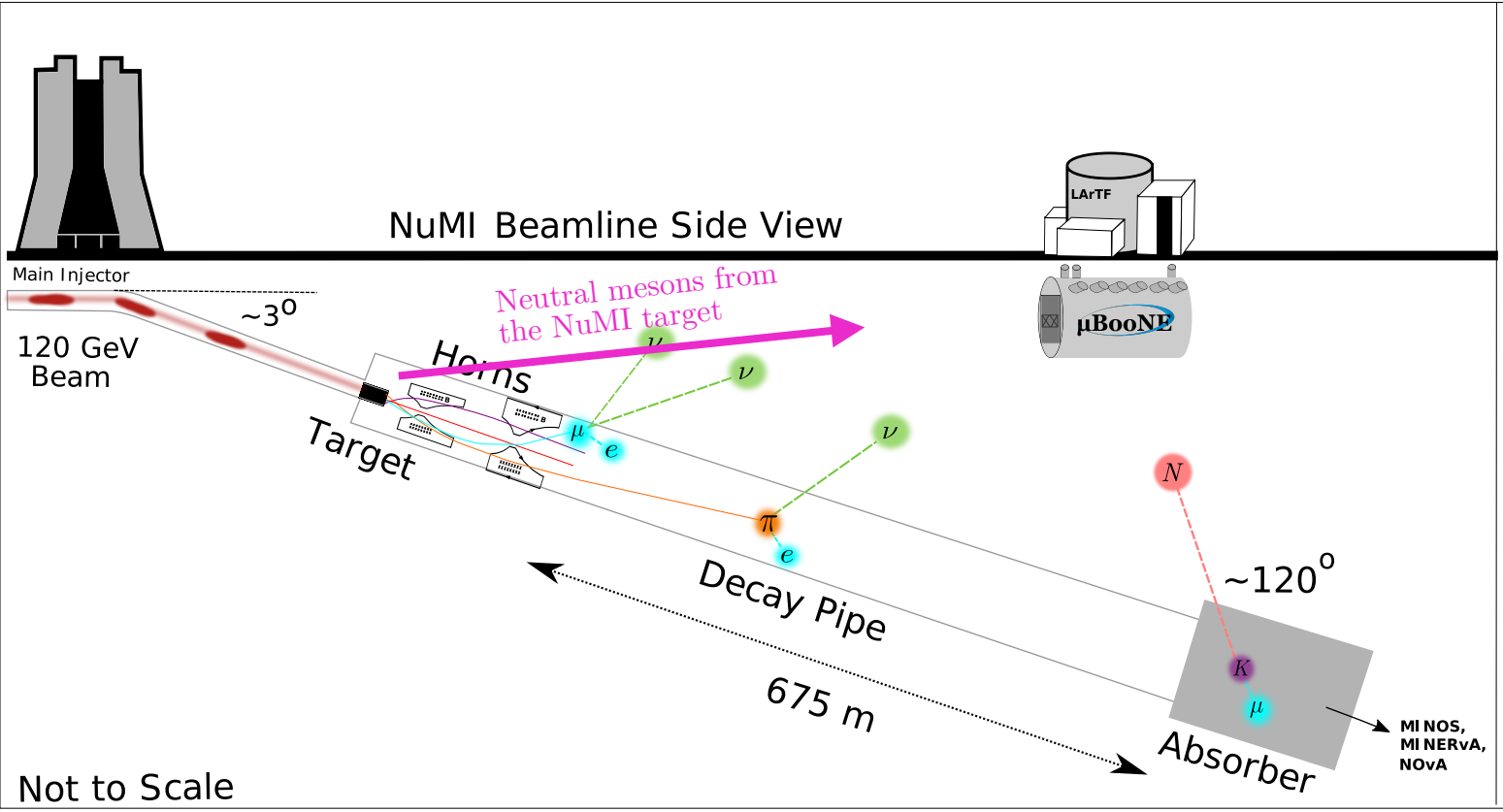
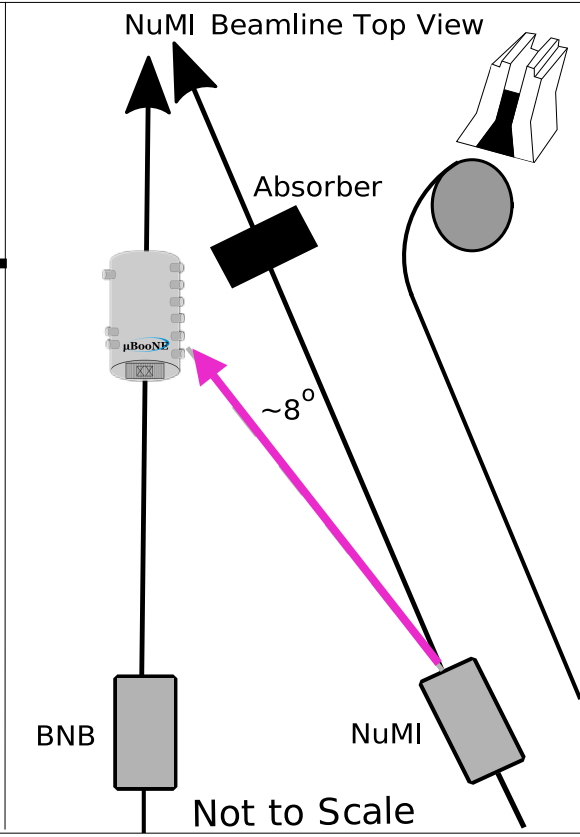
The MicroBooNE experiment at Fermilab



Liquid argon time projection chamber (LArTPC) neutrino detector ($2.6 \times 2.3 \times 10.4$ m^3).
Oldest detector in the Short-baseline Neutrino Program (largest dataset of ν-Ar interactions 2015-2020).
On axis w.r.t. the Booster Neutrino Beam, its main goal is to investigate MiniBooNE low-energy excess.
Today we will focus on exotic searches using NuMI.

Neutrinos from the Main Injector (NuMI) neutrino beam





NuMI beam gives us valuable directionality information

Neutral mesons decay promptly in the target

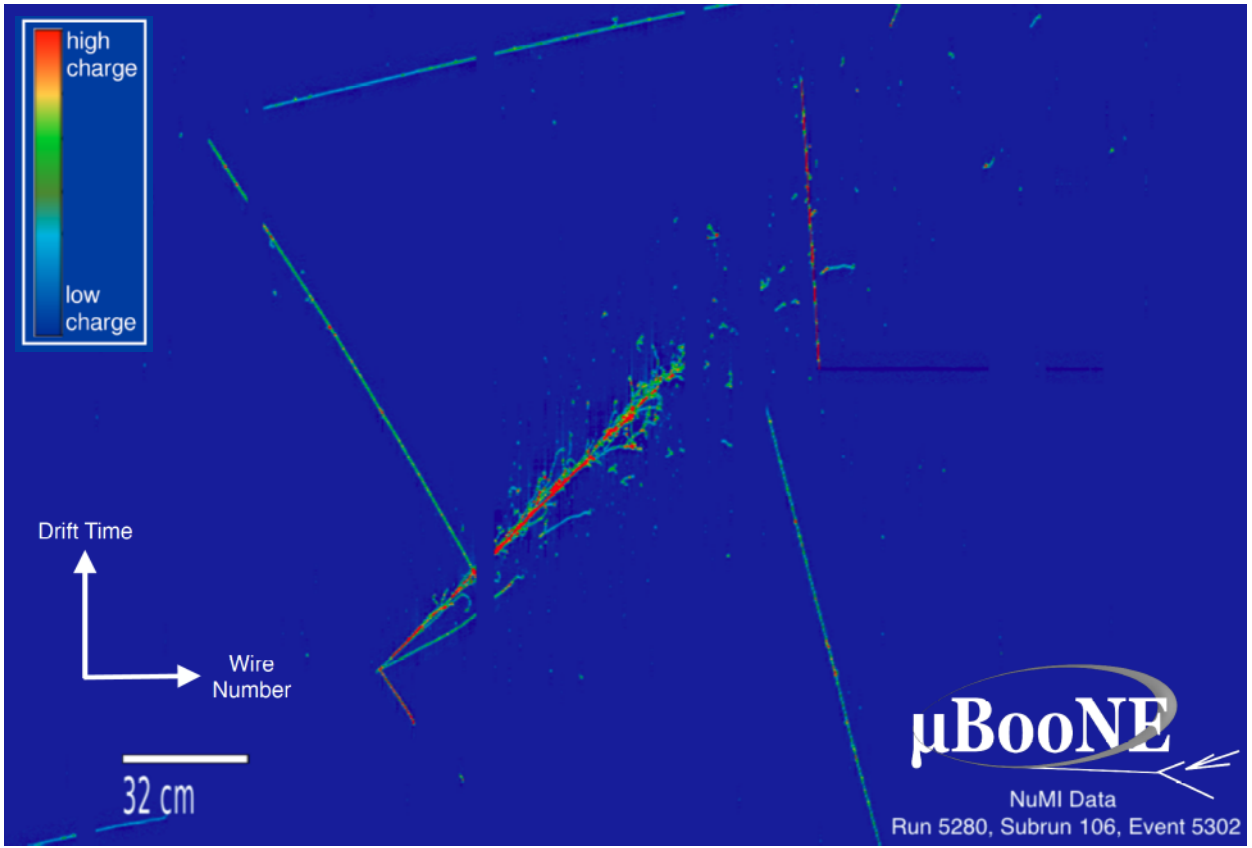
13% of beam protons don't interact with the target → kaons at the absorber (~100 m from MicroBooNE).

LArTPC – event display

LArTPC: Digital bubble-chamber

3 planes of wires for charge readout + photon detection system

→ 3D reconstruction and calorimetry



Phys. Rev. D 103, 052002

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Heavy Neutral Leptons (HNL)

Extension of the PMNS matrix

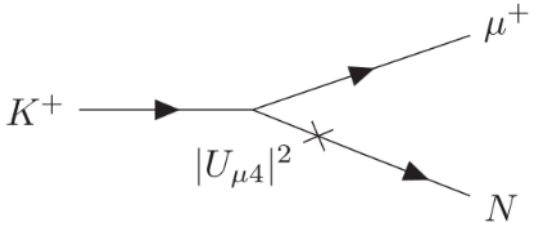
Standard mixing

New physics

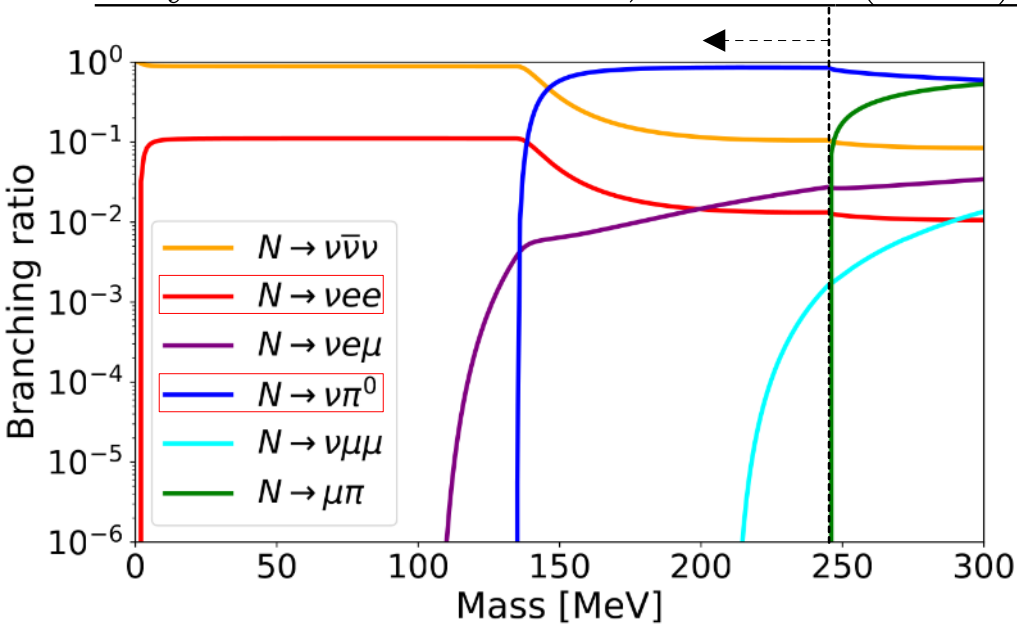
$$U^{\text{Extended}}_{\text{PMNS}} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U^{3\times 3}_{\text{PMNS}}} \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \\ \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \begin{pmatrix} \\ \\ \\ \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{pmatrix}$$

We set $|U_{e4}|^2 = |U_{\tau 4}|^2 = 0$ and place limits on $|U_{\mu 4}|^2$

Produced by decay of kaons at NuMI absorber

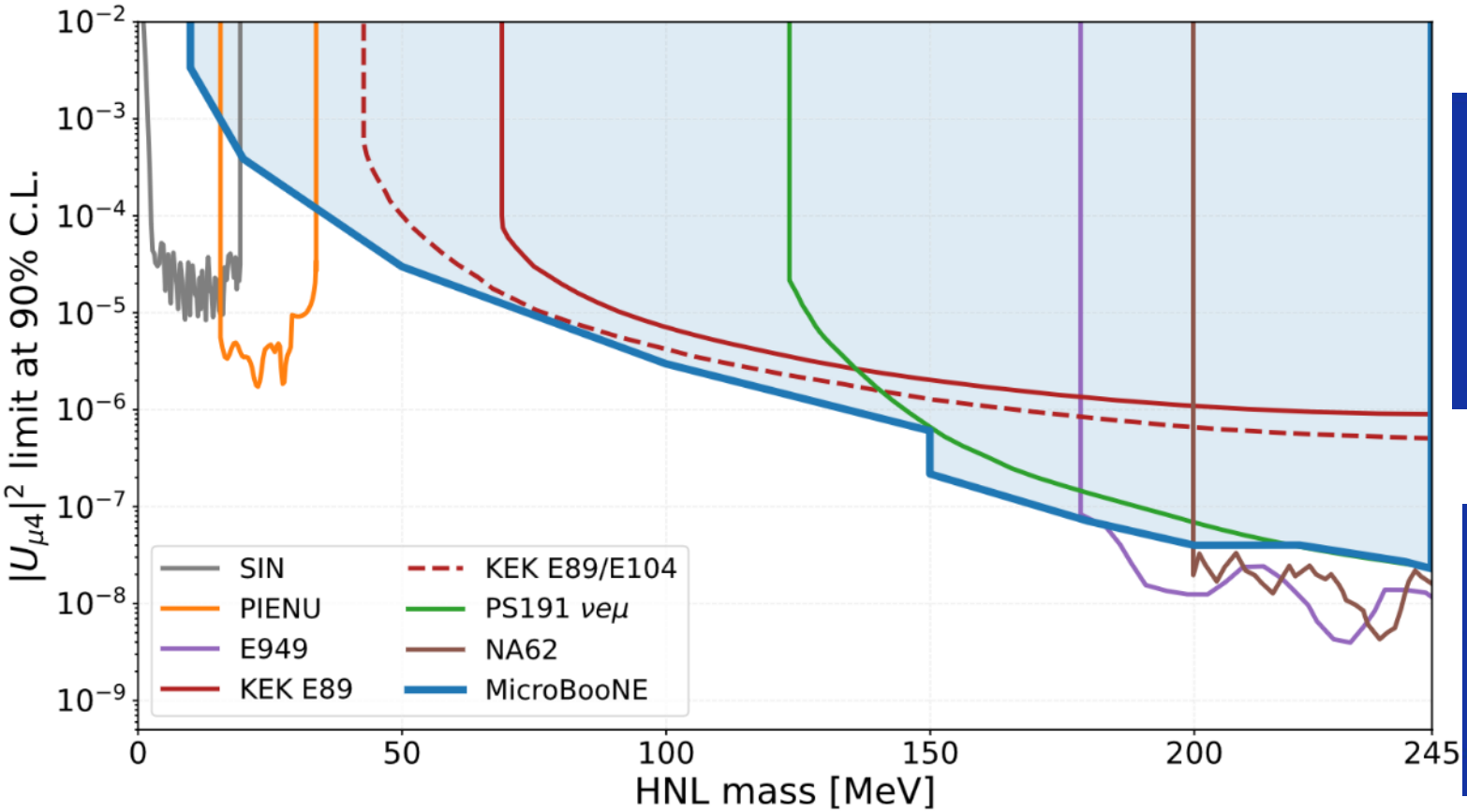


Our latest search:
Phys. Rev. Lett. 132, 041801 (2024)



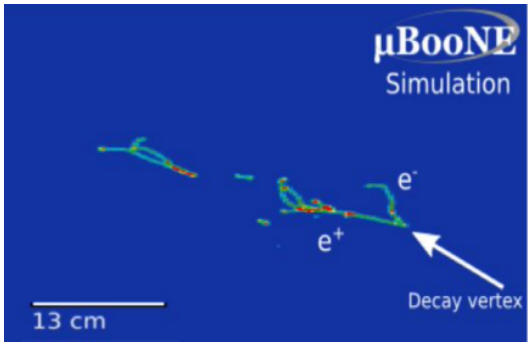
HNL results ($N \to \nu e^+ e^-$ $N \to \nu \pi^0$)

Our latest HNL search: Phys. Rev. Lett. 132, 041801 (2024)

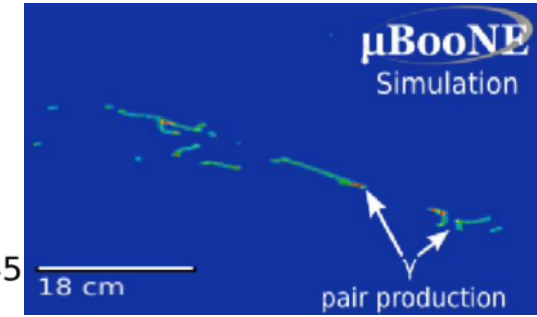


First search in a LArTPC for:

$N \to \nu e^+ e^-$



$N \to \nu \pi^0$

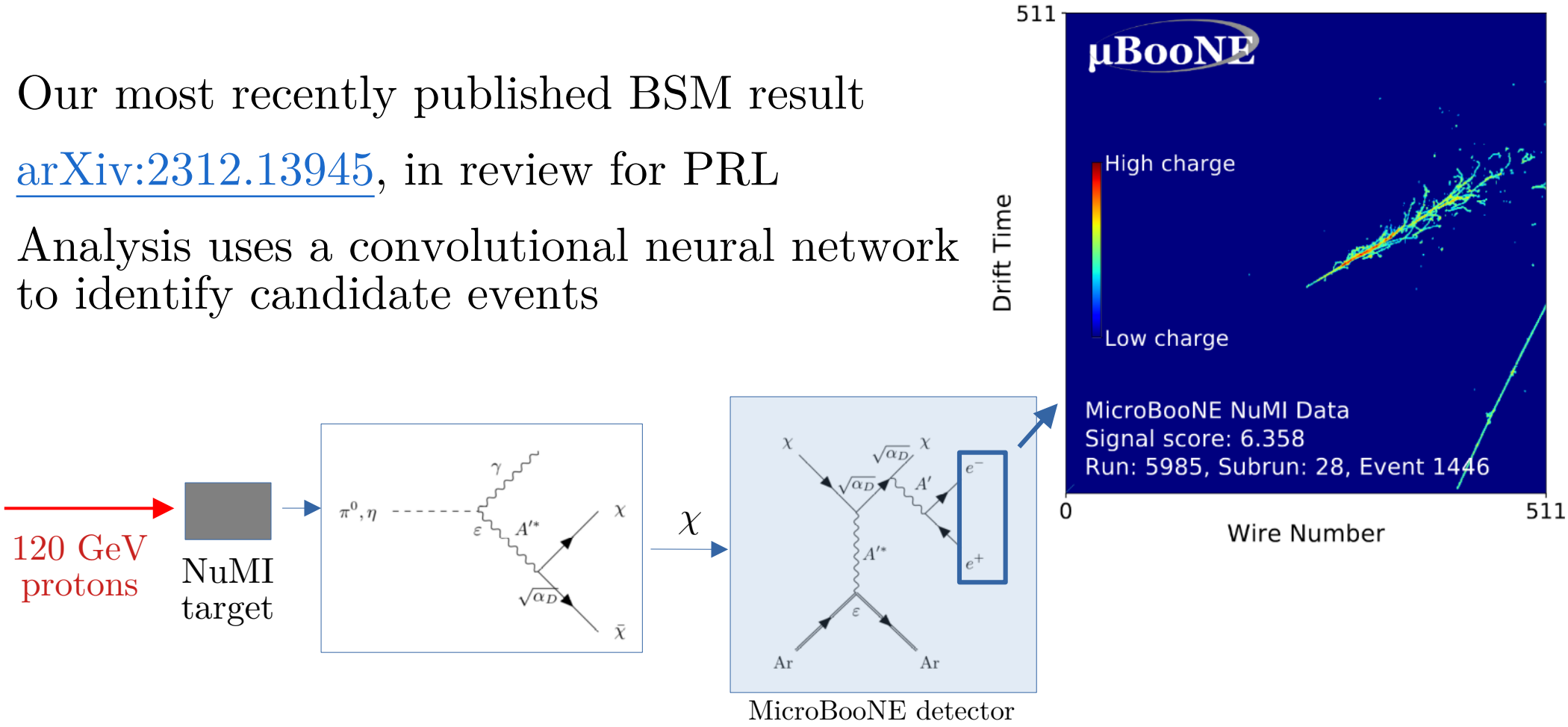


Dark Tridents

Our most recently published BSM result

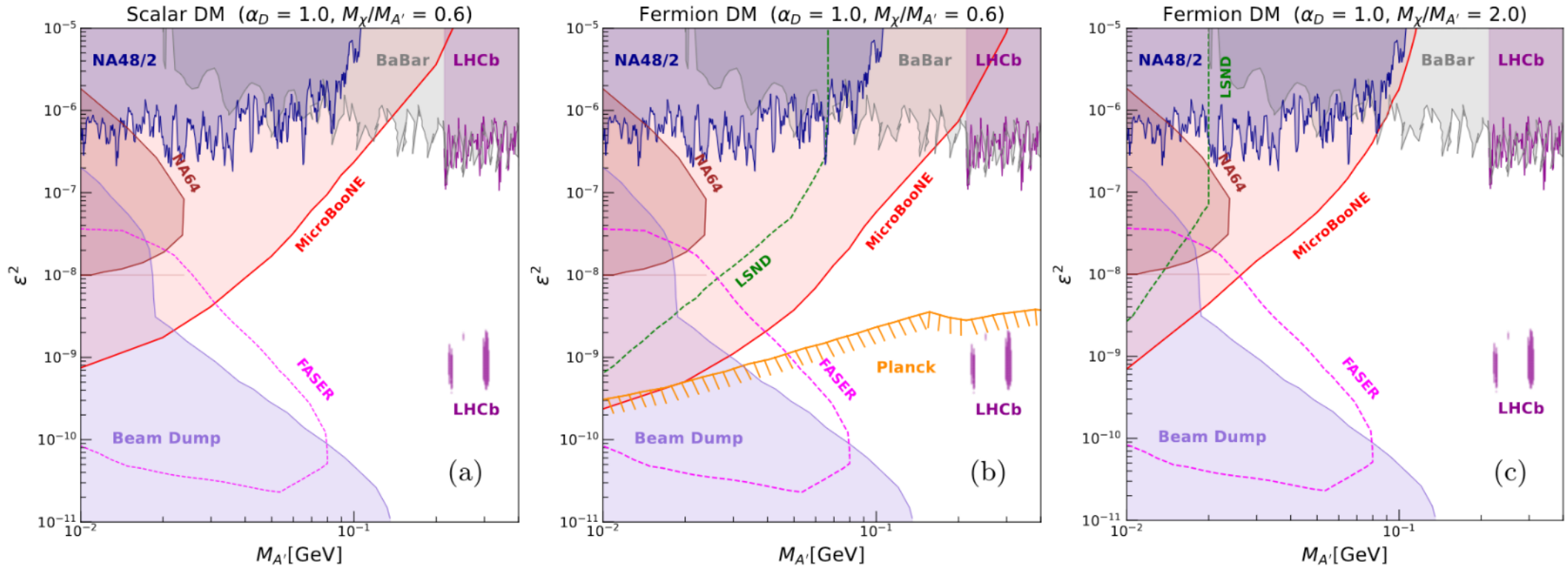
arXiv:2312.13945, in review for PRL

Analysis uses a convolutional neural network to identify candidate events



Dark Tridents results

New limits for two benchmark models $M_\chi/M_{A'} = 0.6$ and 2.0



arXiv:2312.13945

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Other MicroBooNE BSM searches

MeV scale physics

Graphics from https://indico.fnal.gov/event/62104/

New reconstruction product: blips

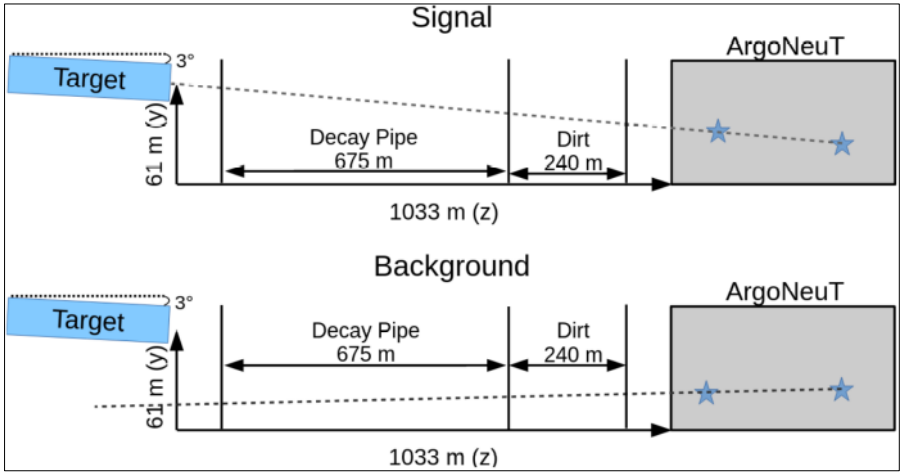
LArTPCs can probe new energy range

JINST 17 P11022 (2022)
Phys. Rev. D 109, 052007 (2024)

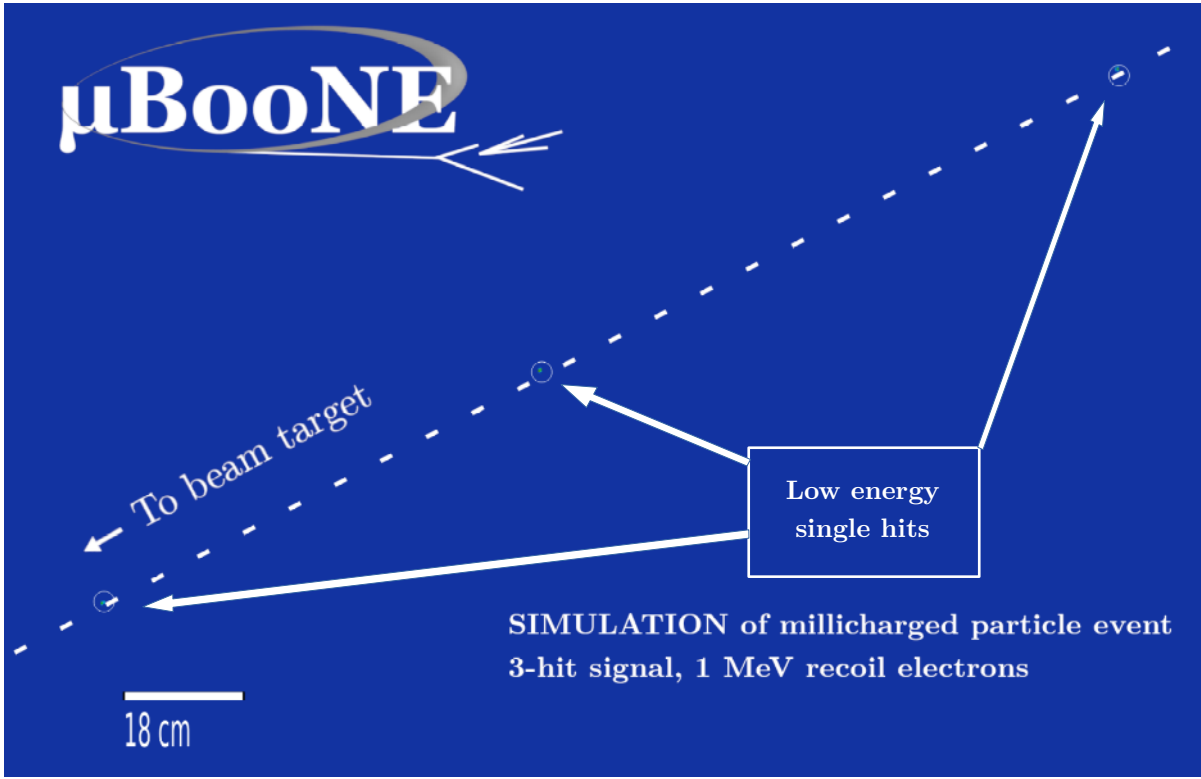
Millicharged particles (coming later this year)

Millicharged particles: feebly interacting long-lived particles with fractional charge

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



ArgoNeuT: Phys. Rev. Lett. 124, 131801



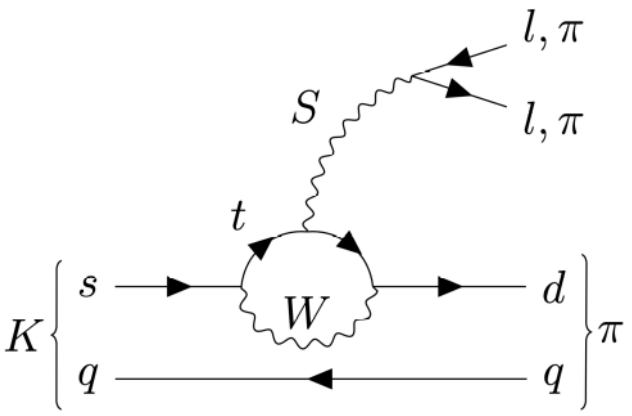
Isolated hits with argon electron in a straight line. Favours low-energy hits.

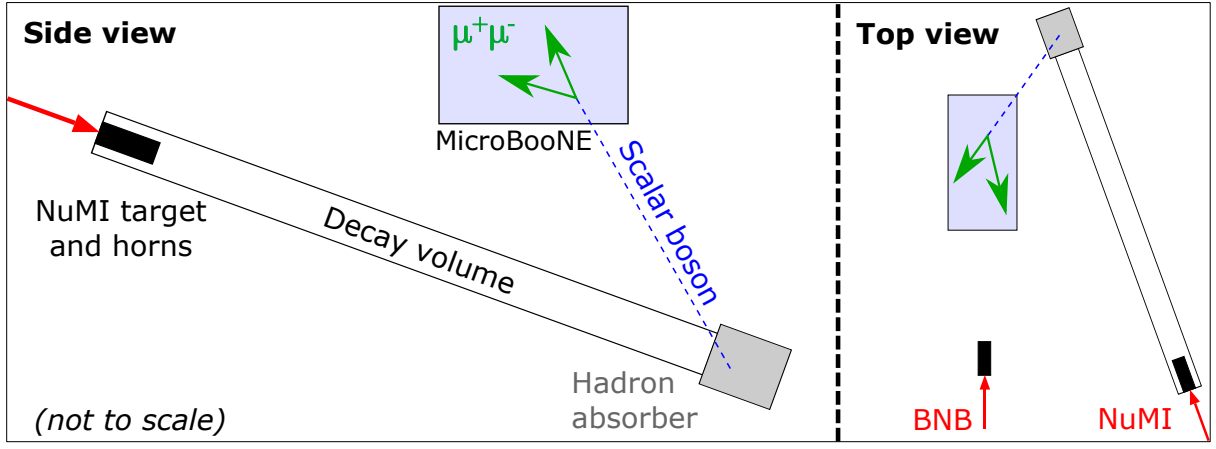
Higgs Portal Scalars (HPS)

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 $\sin(\theta) \rightarrow \theta$



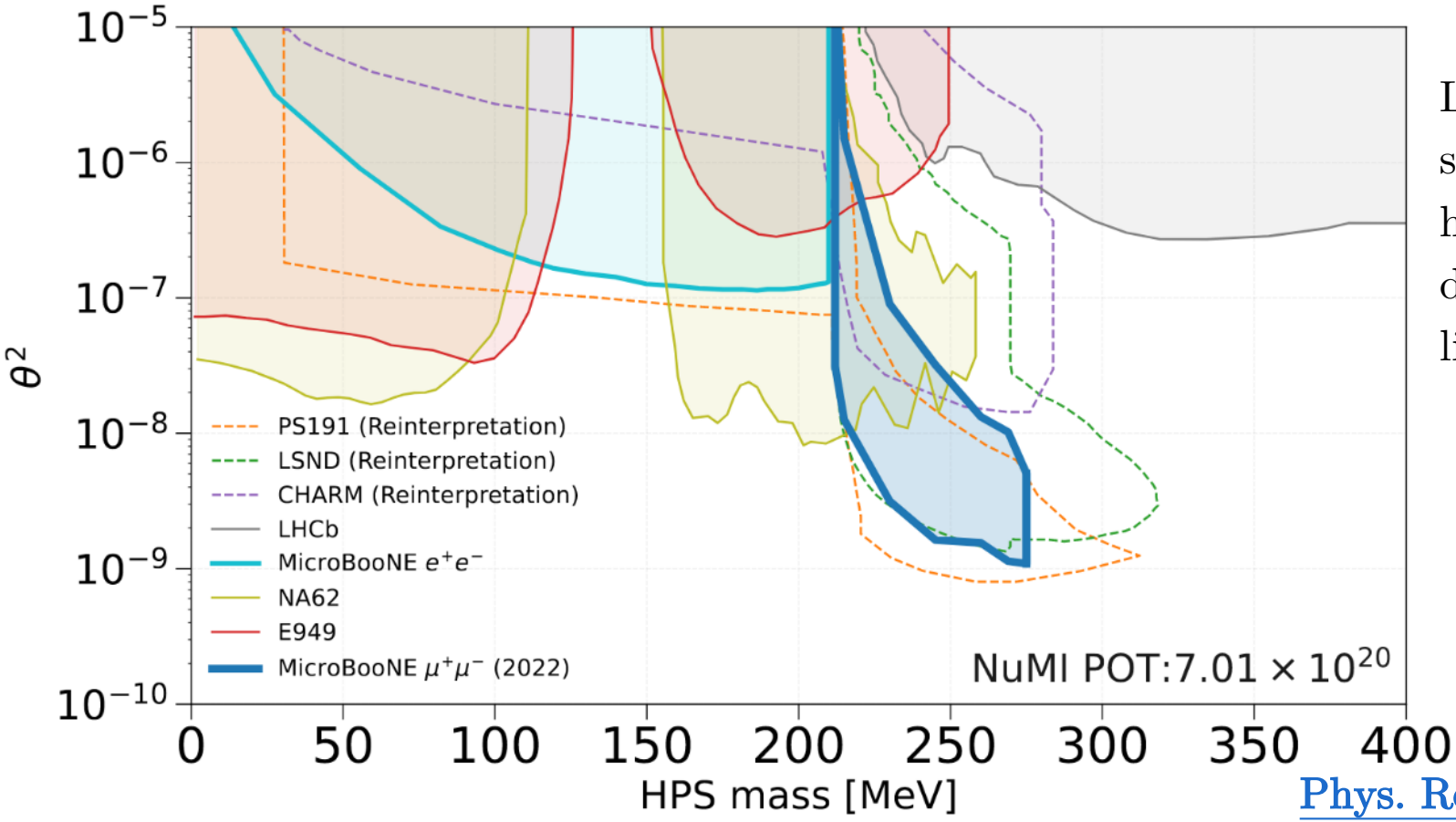


Production via Kaon decay at rest in the NuMI absorber

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

MicroBooNE searches: e^+e^- 2021, $\mu^+\mu^-$ 2022 → Phys. Rev. Lett. 127, 151803; Phys. Rev. D 106, 092006

MicroBooNE HPS results

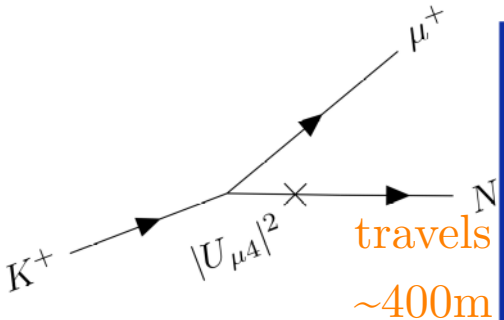


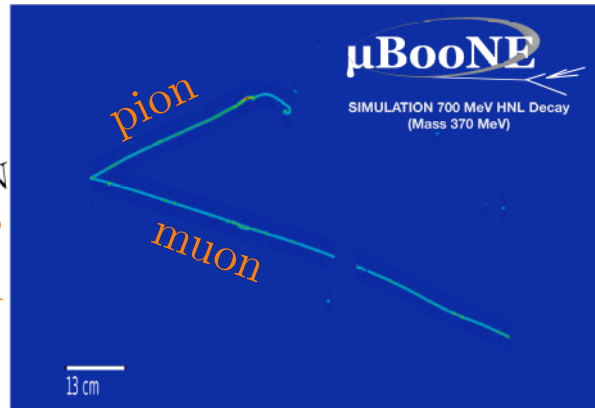
Lack of sensitivity at high coupling due to short lifetime

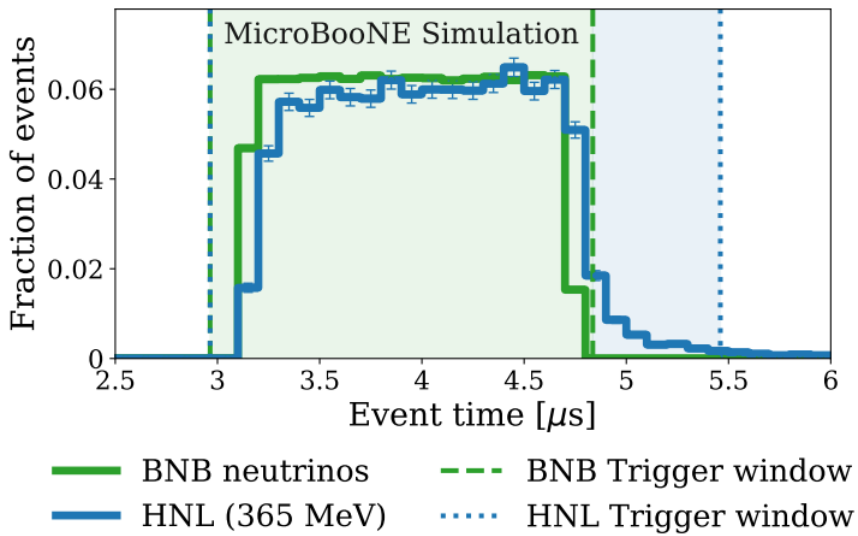
Phys. Rev. Lett. 127, 151803
Phys. Rev. D 106, 092006

MicroBooNE first HNL search (2020) (BNB $N \to \mu^{\pm}\pi^{\mp}$)

- Phys. Rev D 101, 052001
- First search of HNLs in LArTPCs
- Produced at **BNB**
- Novel "late trigger" window
  - HNLs take longer than neutrinos to travel → effectively removed neutrino background
- Limits for 260-385 MeV

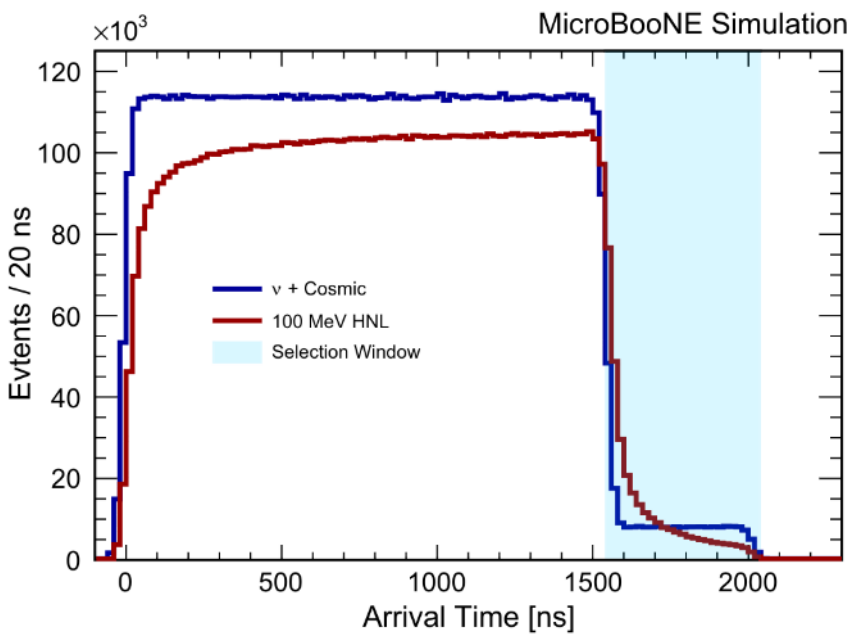


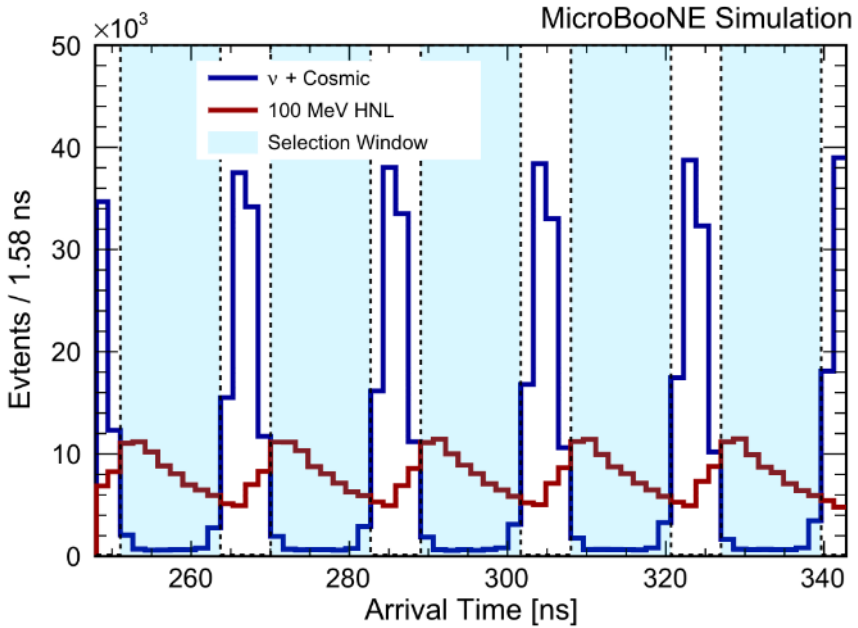




Late trigger window potential improvement with ns timing

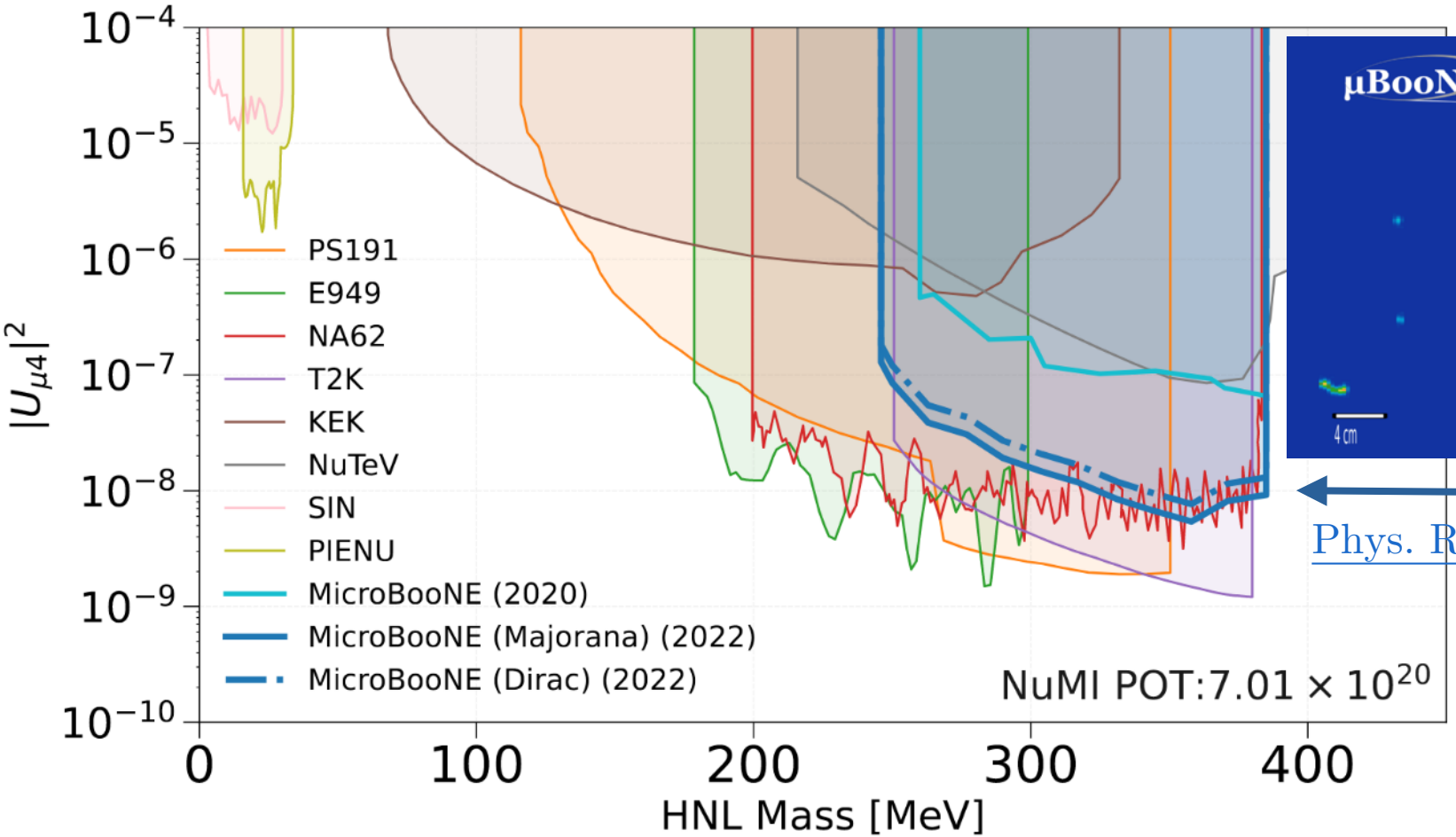
Recent calibration improvements allow MicroBooNE to achieve timing resolution of order 1ns revealing the BNB bunch substructure

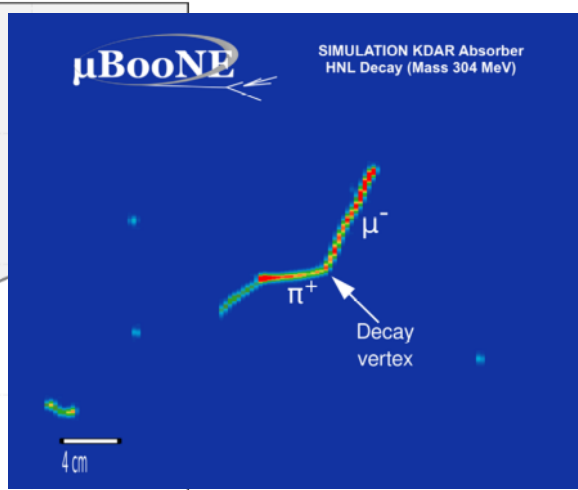




Phys. Rev. D 108, 052010 (2023)

MicroBooNE HNL results (2022) (NuMI $N \to \mu^{\pm}\pi^{\mp}$)

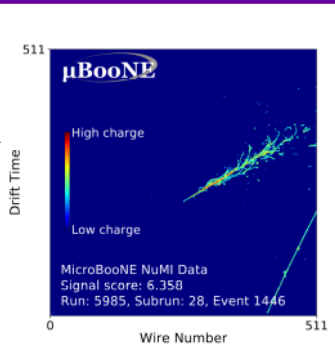


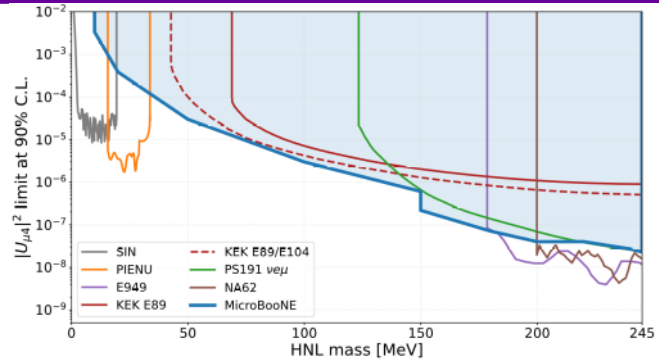


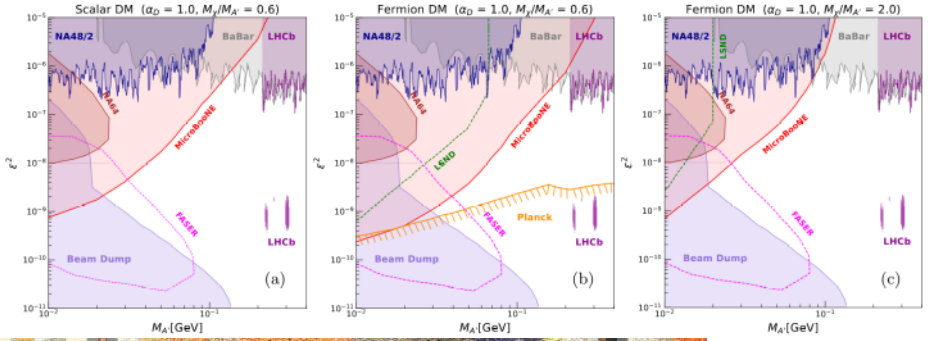
Phys. Rev. D 106, 092006

Summary

- MicroBooNE is much more than just a neutrino detector
- LArTPCs can be used to search for diverse topologies and have great performance
- Shown latest results of BSM searches
  - Third iteration of HNL results
  - First search for dark tridents on a LArTPC
- MicroBooNE has a rich BSM search program
- Always something in the works! Stay tuned for…
  - Millicharged particles
  - Heavy QCD axions
  - More Higgs Portal Scalars
  - Next generation of LArTPCs!



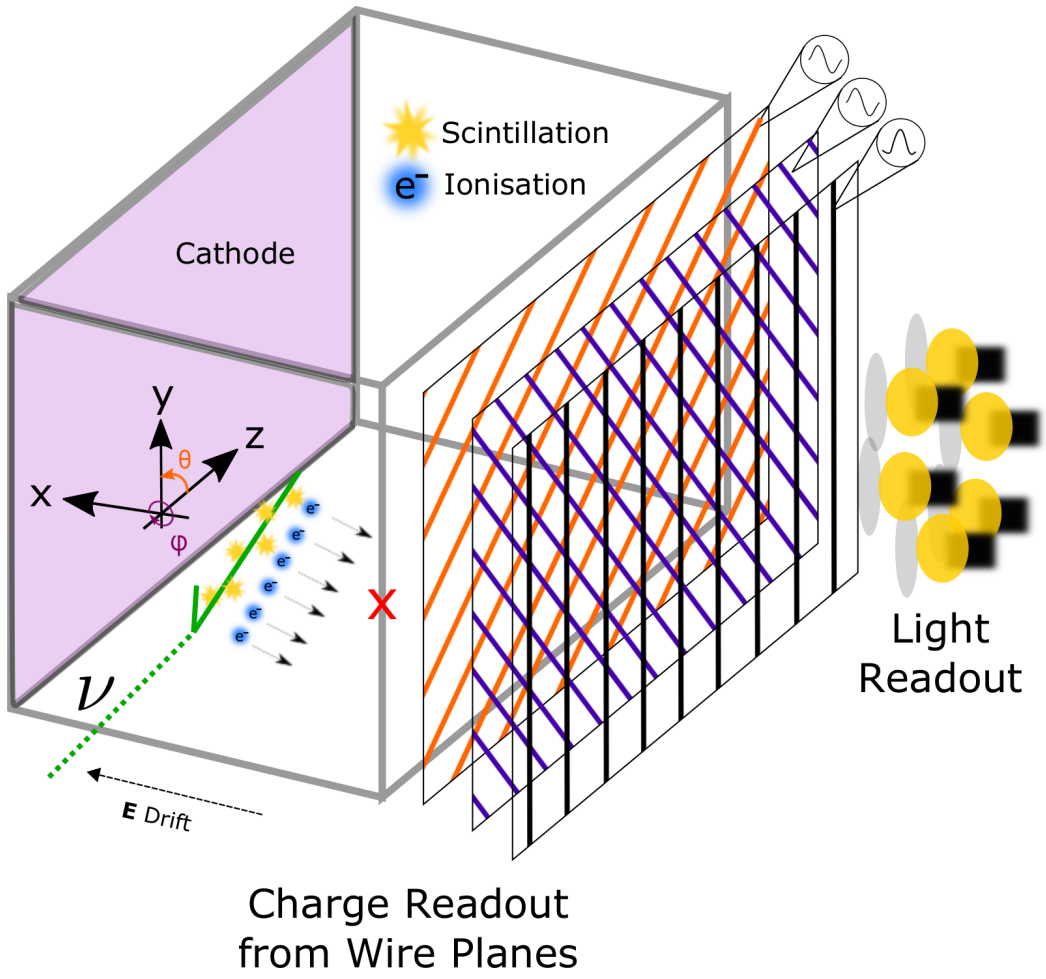




MicroBooNE collaboration meeting at Manchester (Jan 2024)

Backup

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

HNL 2024 kinematics

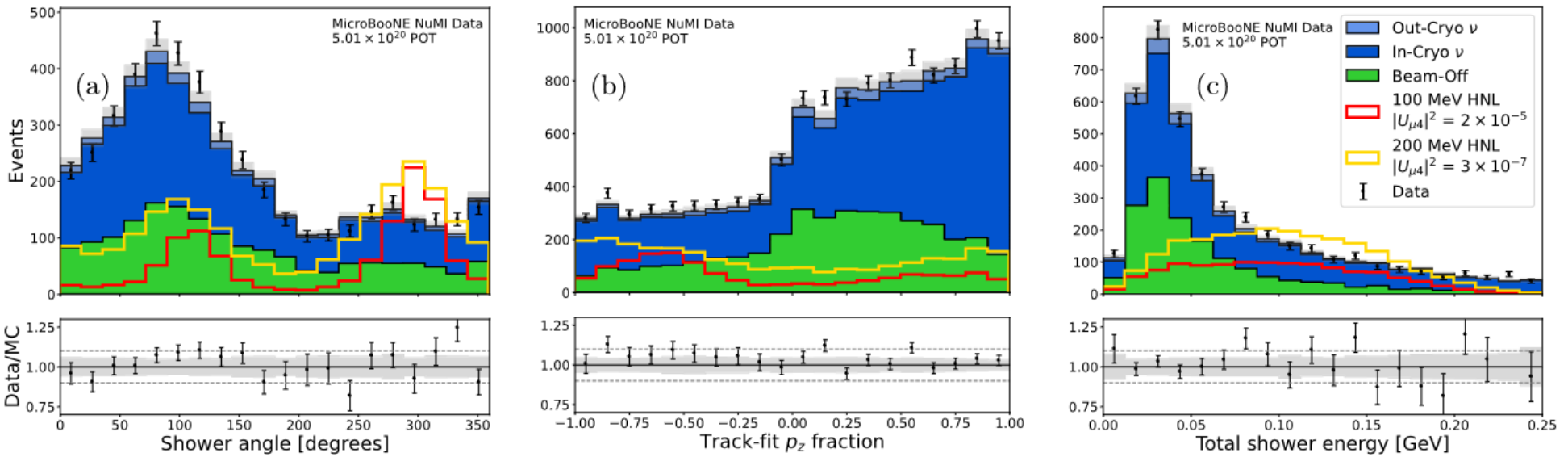


FIG. 2. BDT input variables after the preselection for run 3 (RHC) data: (a) shower angle θ_{yz} with respect to the y axis projected on the yz plane, (b) track-fit z momentum fraction, and (c) the total shower energy for data and the background prediction. The signal distributions for $N \to \nu e^+ e^-$ decays with $m_{\mathrm{HNL}} = 100$ MeV and $N \to \nu \pi^0$ decays with $m_{\mathrm{HNL}} = 200$ MeV are normalized to $|U_{\mu 4}|^2 = 2 \times 10^{-5}$ and $|U_{\mu 4}|^2 = 3 \times 10^{-7}$, respectively. The gray band indicates the quadrature sum of all uncertainties on the background expectation.

Phys. Rev. Lett. 132, 041801 (2024)

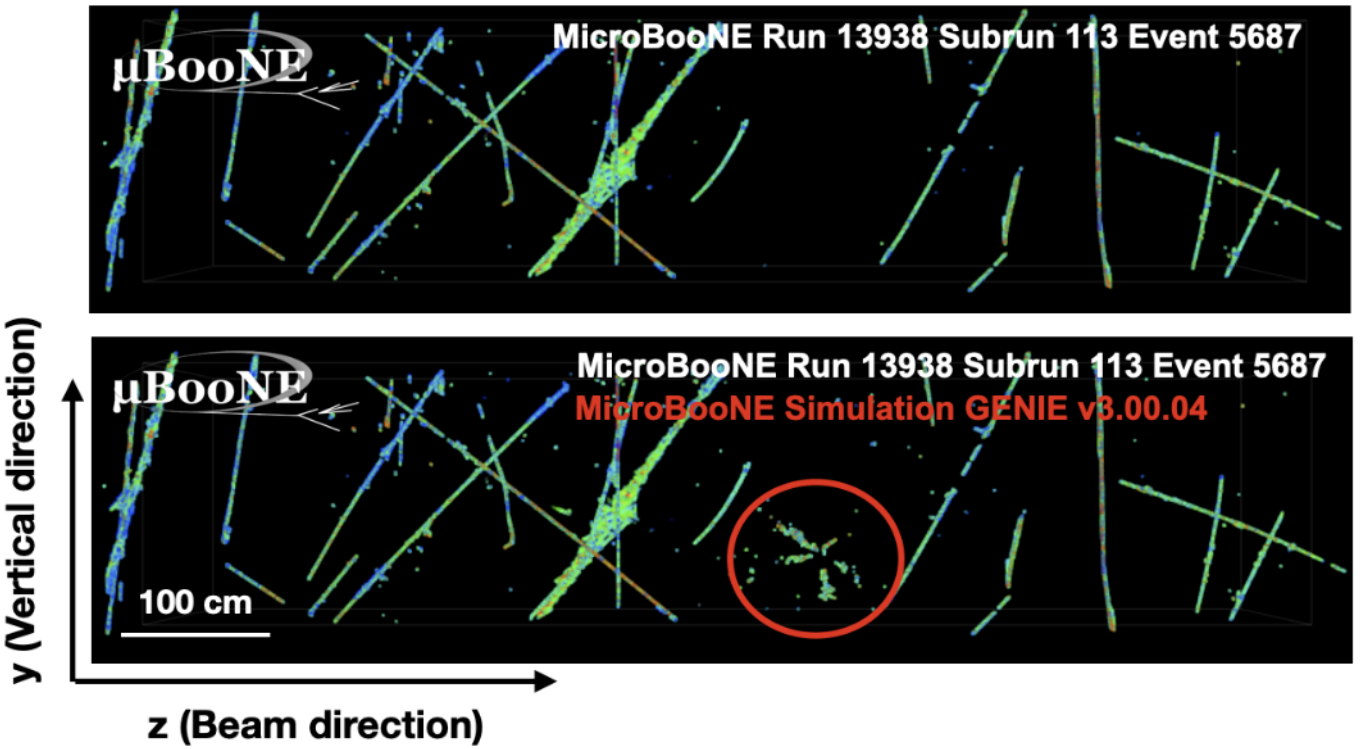
Neutron-antineutron oscillations

arXiv:2308.03924
(submitted to JINST)

Neutron oscillates into antineutron and annihilates with nearby neutrons, resulting in a "star" topology (not coming from any beam!)

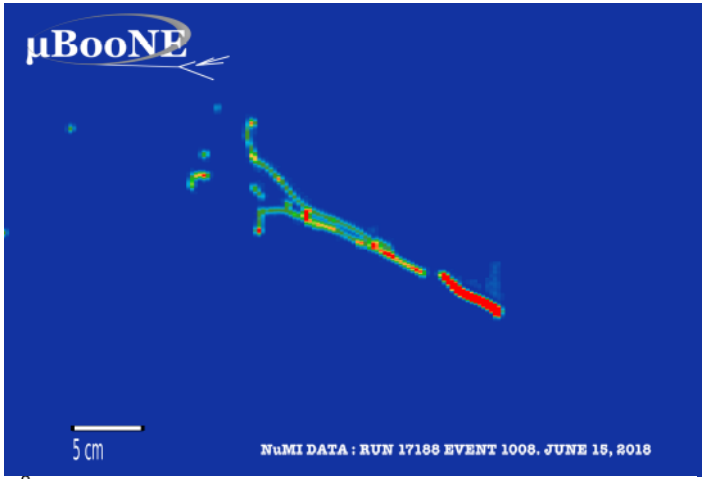
Uses deep learning methods to select candidate events, achieving ~70% efficiency.

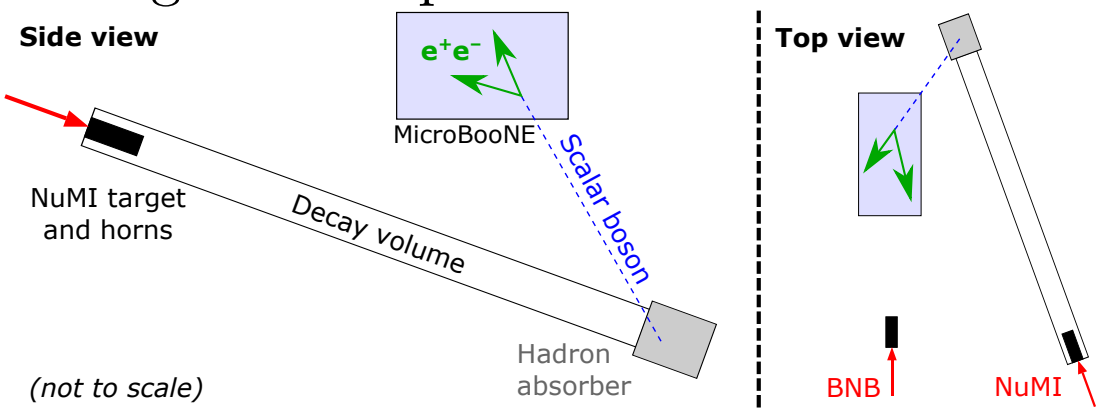
First demonstration of such a search in a LArTPC, serves as proof-of-principle for future LArTPCs

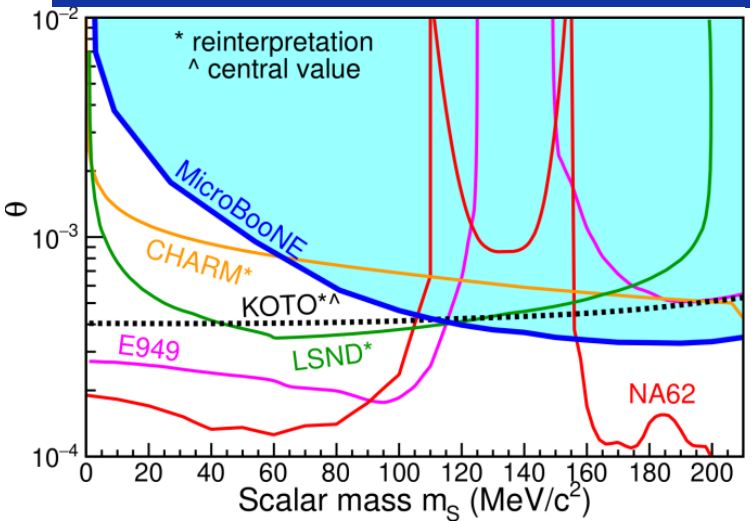


MicroBooNE HPS search (2021)

- 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



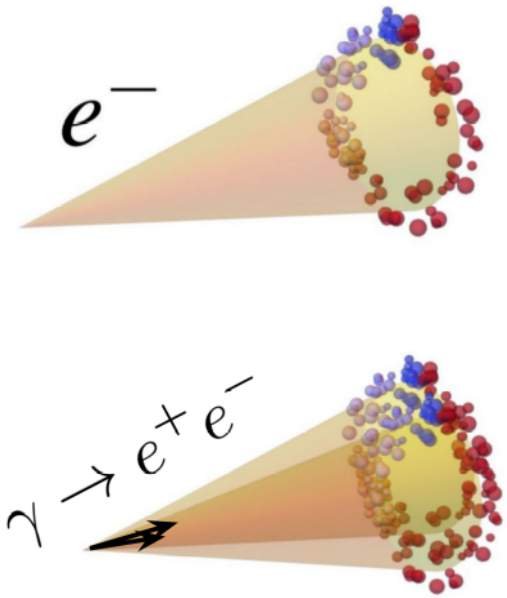


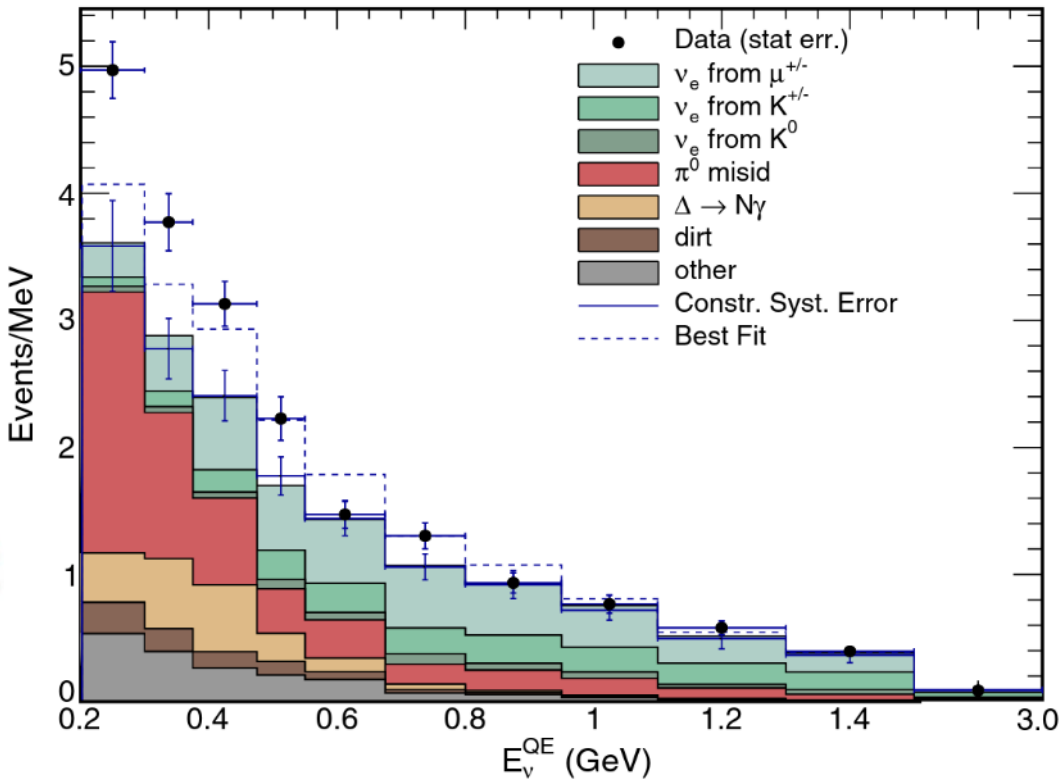


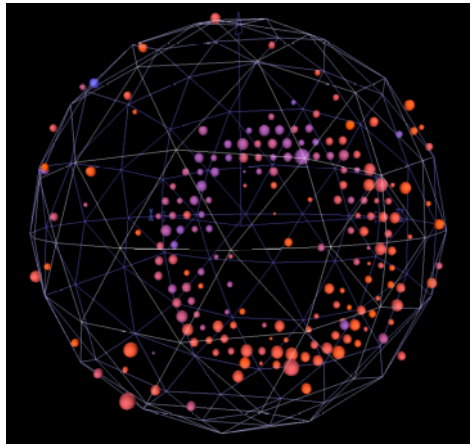
MiniBooNE low-energy excess (LEE)

MiniBooNE (2002-2019) observed a LEE of electromagnetic events with 4.8σ significance.

As a Cherenkov detector MiniBooNE is unable to distinguish between electrons and photons.







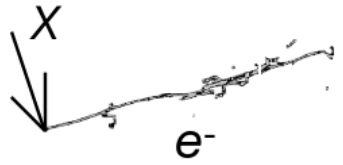
MicroBooNE search for the MiniBooNE low-energy excess

Searches using multiple topologies and reconstruction methods: Phys. Rev. Lett. 128, 241801
We found no evidence of a ν_e excess

Phys. Rev. D 105, 112003

Phys. Rev. D 105, 112004

Phys. Rev. Lett. 128, 111801



Phys. Rev. D 105, 112005

Overlapping e^+e^-

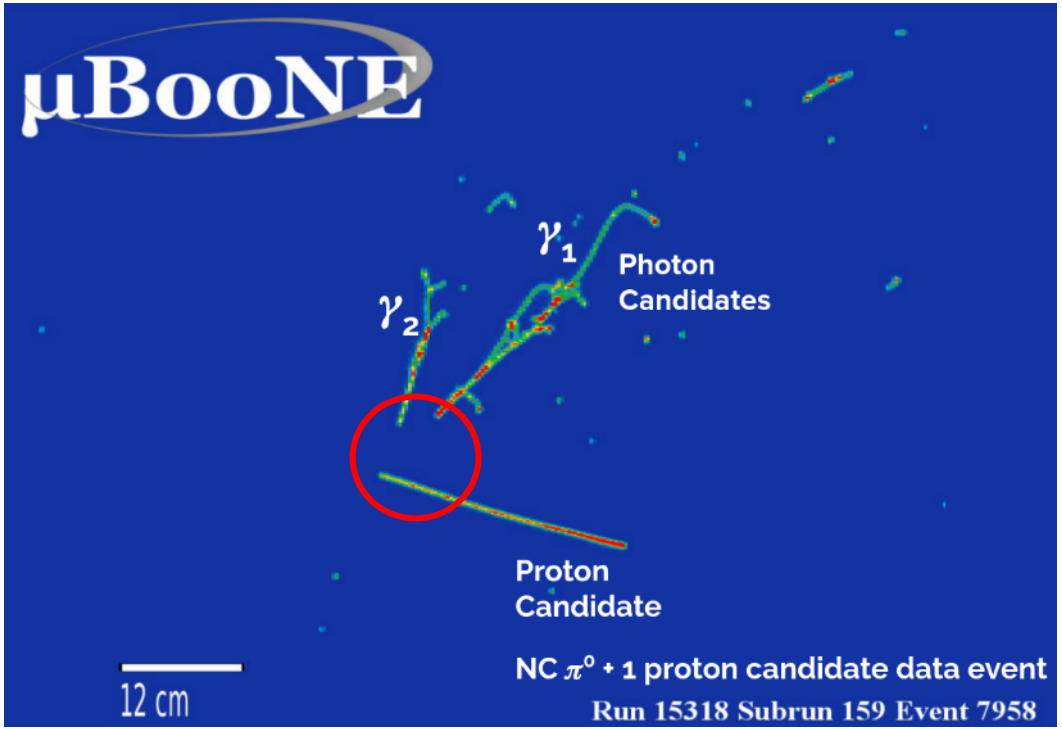
Overlapping e^+e^-

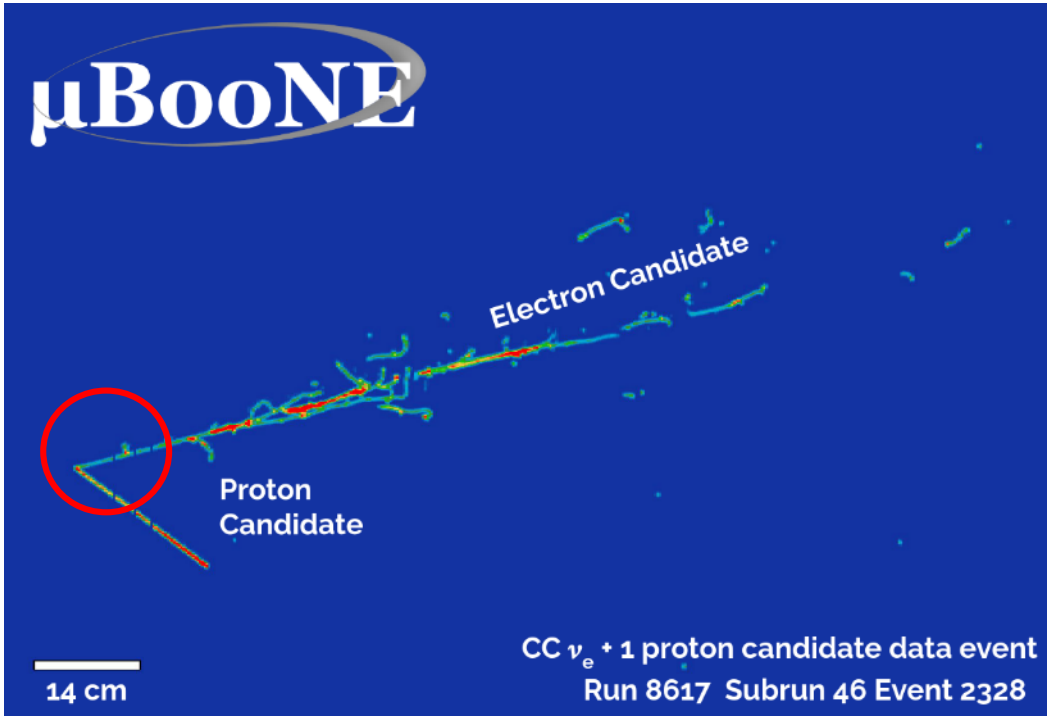
Highly asymmetric e^+e^-

Highly asymmetric e^+e^-

To be explored!

Electron/photon separation in LArTPCs

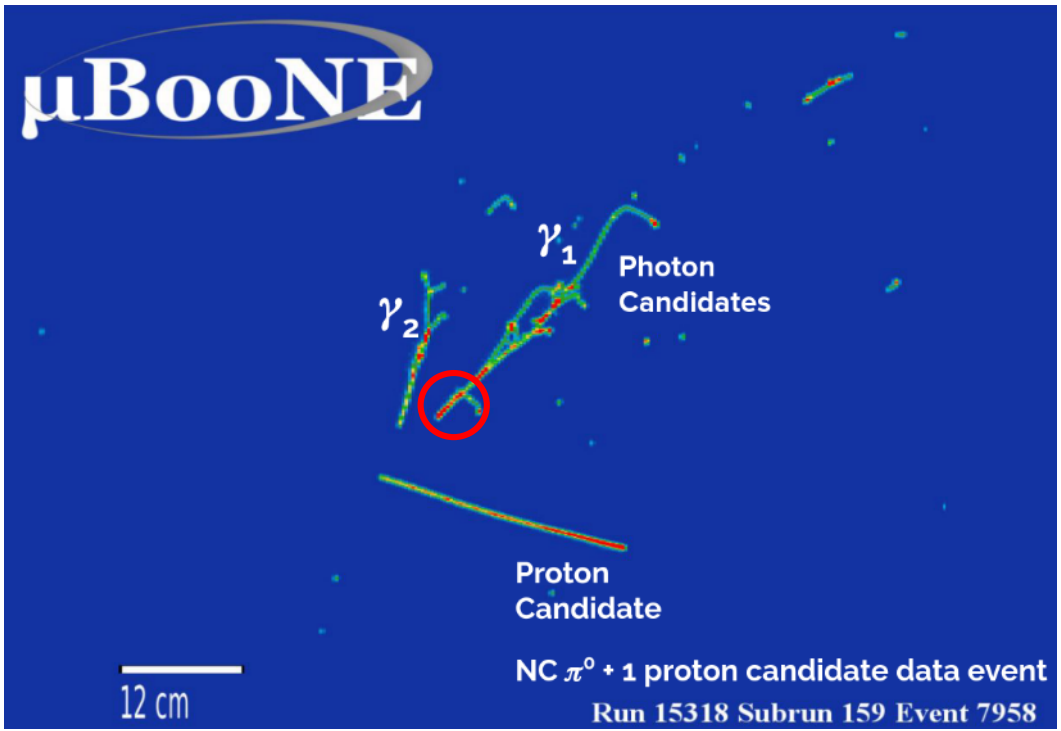


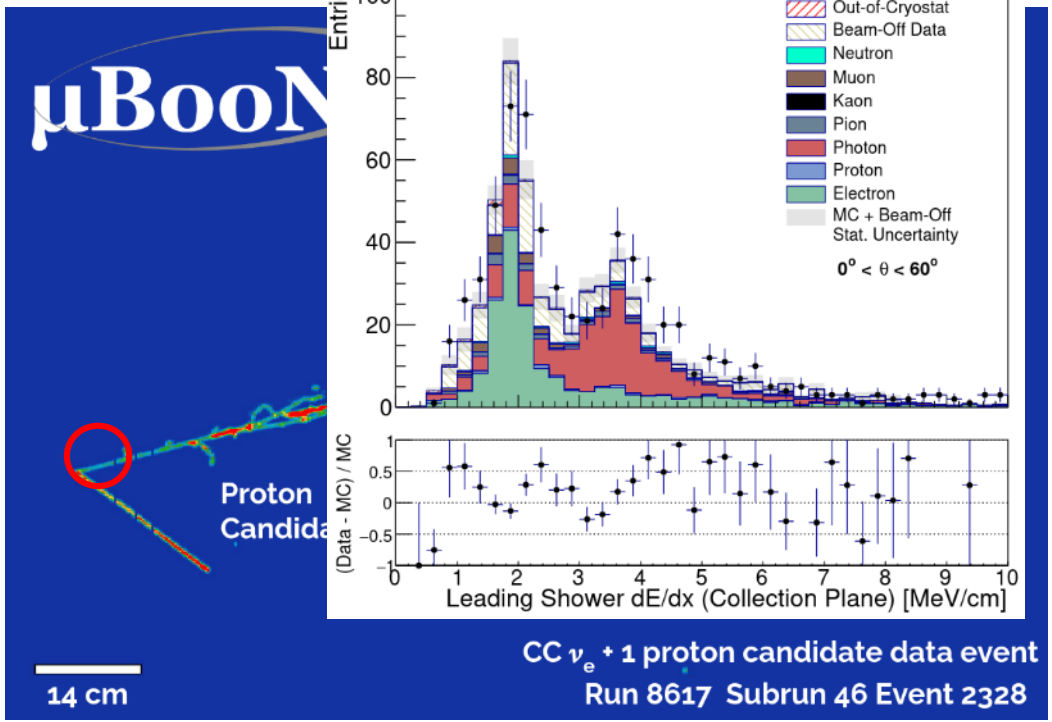


Photon initiated showers have distinct gap between interaction vertex and start of the shower, electrons do not.

Electron/photon separation in LArTPCs

Phys. Rev. D 104, 052002





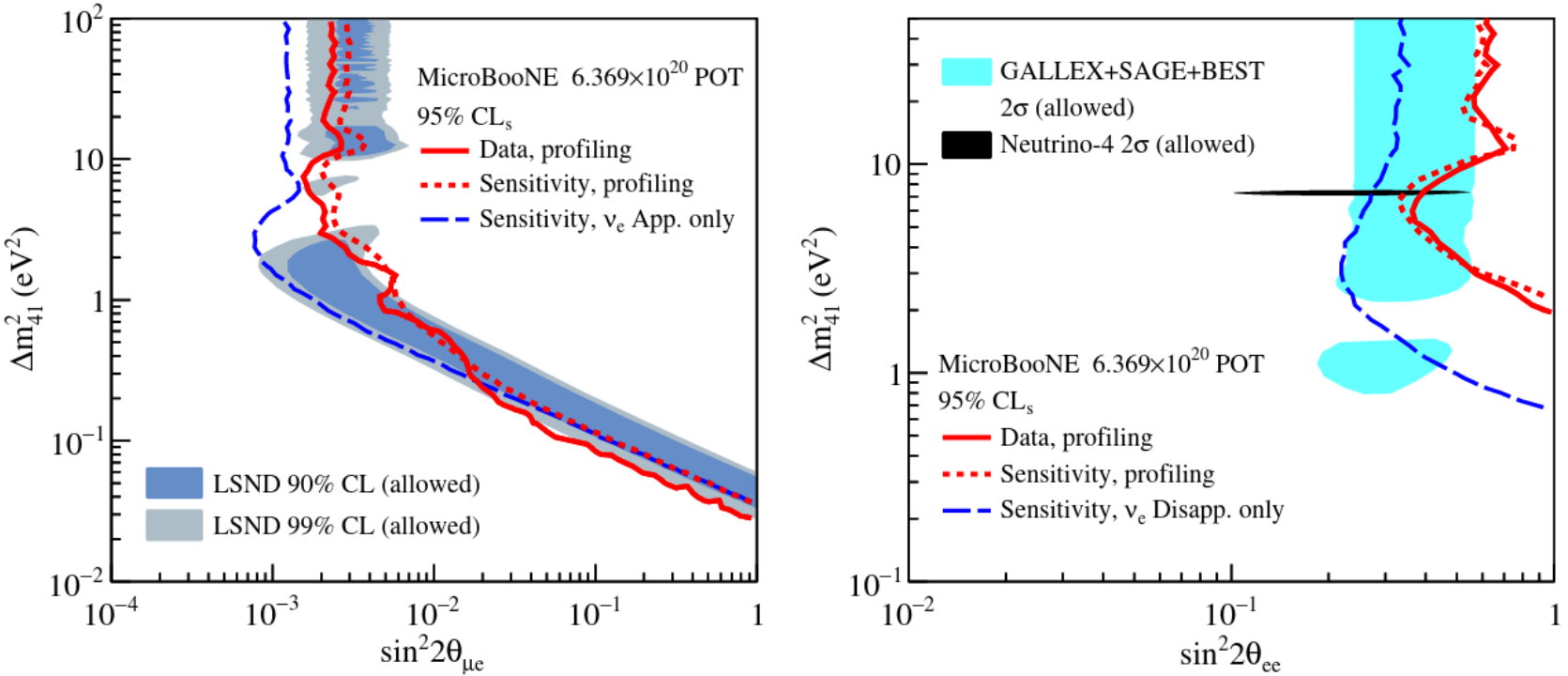
Starting segment of photon initiated shower has double the deposited charge ($\gamma \rightarrow e^+e^-$)

3+1 light sterile search

Phys. Rev. Lett. 130, 011801

Full 3+1 search, extended 4x4 PMNS matrix, relevant elements $|U_{e4}|^2$, $|U_{\mu 4}|^2$, $|U_{s4}|^2$, oscillation parameters Δm^2_{41}, $\sin^2\theta_{14}$, $\sin^2\theta_{24}$

Data consistent with 3ν hypothesis. Limiting factor is degeneracy on ν_e disappearance and appearance, will be addressed using NuMI beam



MicroBooNE data