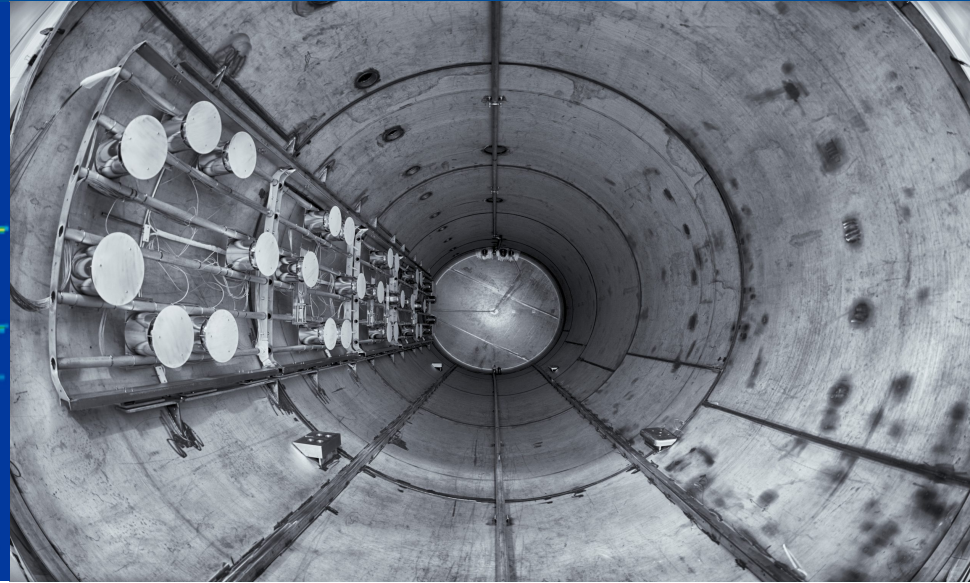


The logo for the MicroBooNE experiment, featuring the text "μBooNE" in a stylized font with a white underline and a small graphic of a particle track to the right.

10 cm

BNB Run: 16341 Subrun: 27 Event: 1359



MicroBooNE – Overview of Recent Results

Vincent Basque For the MicroBooNE Collaboration

NuPhys 2023 @ King's College London

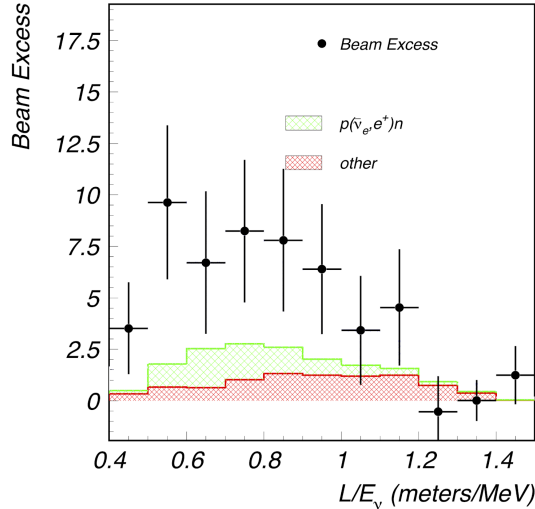
19/12/2023



Low Energy Excess (LEE) and You – Anomalies

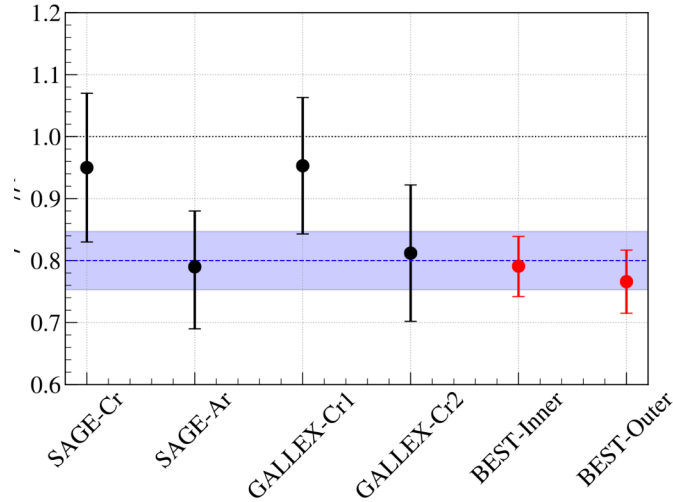


[Phys. Rev. D 64, 112007 \(2001\)](#)



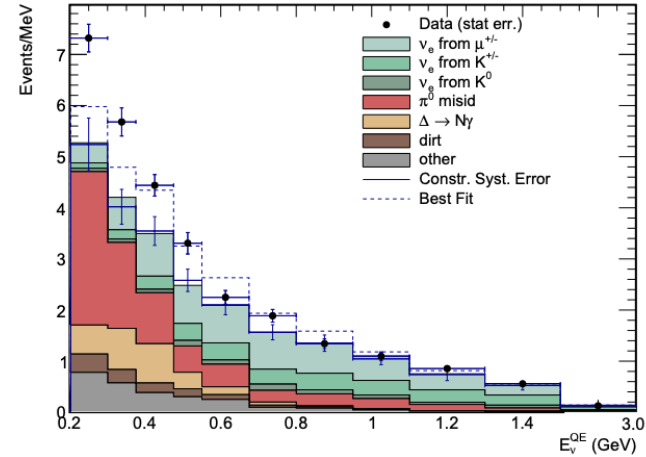
LSND -> stopped pion source.
Observed **excess** of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam.

[Phys. Rev. C 105 6, 065502 \(2022\)](#)



Gallium detectors -> calibration sources in detectors.
Observed **deficit** of ν_e .

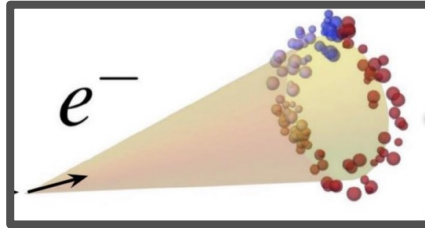
[Phys. Rev. D 103, 052002 \(2021\)](#)



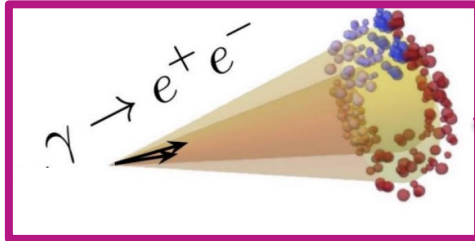
MiniBooNE -> neutrino beam.
Observed **excess** of ν_e ($\bar{\nu}_e$) in a ν_μ ($\bar{\nu}_\mu$) beam.

Low Energy Excess (LEE) and You – MiniBooNE

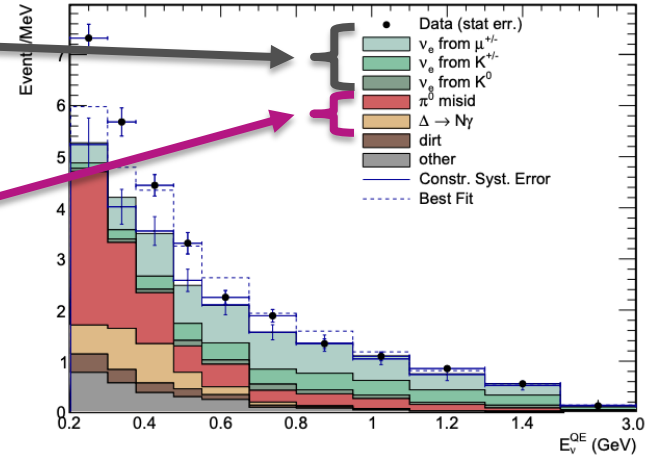
Signal



Background



Phys. Rev. D 103, 052002 (2021)



MiniBooNE is a Cherenkov detector.

Hard to differentiate between electron and photons. Could we use a *new* detector technology instead?

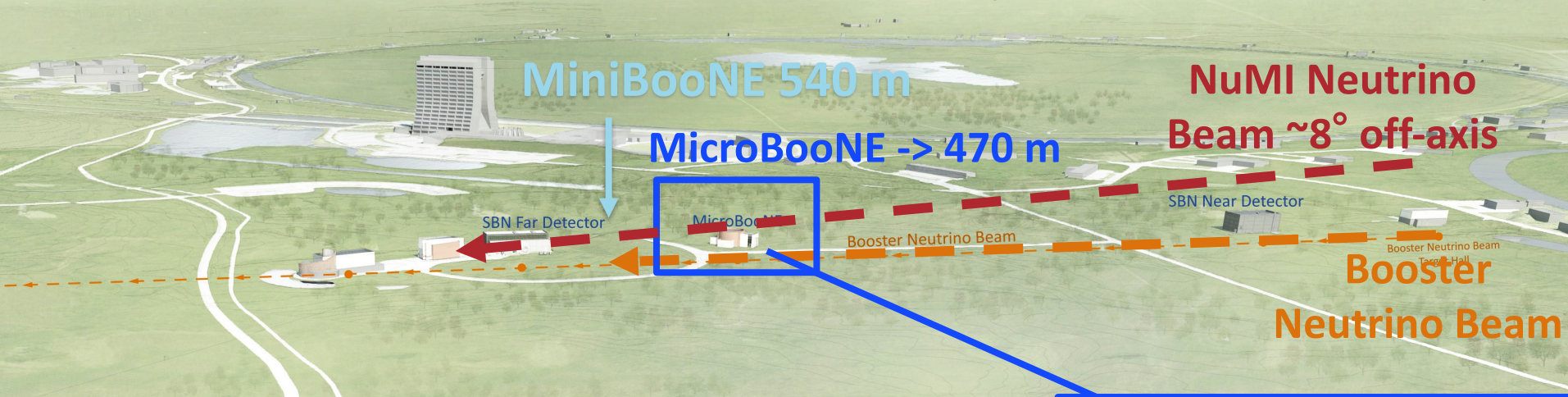
MiniBooNE \rightarrow neutrino beam.
Observed **excess** of ν_e ($\bar{\nu}_e$) in a ν_μ ($\bar{\nu}_\mu$) beam.

MicroBooNE at Fermilab



<https://doi.org/10.1103/PhysRevLett.128.241801>

Fermilab Accelerator Complex and Neutrino Campus



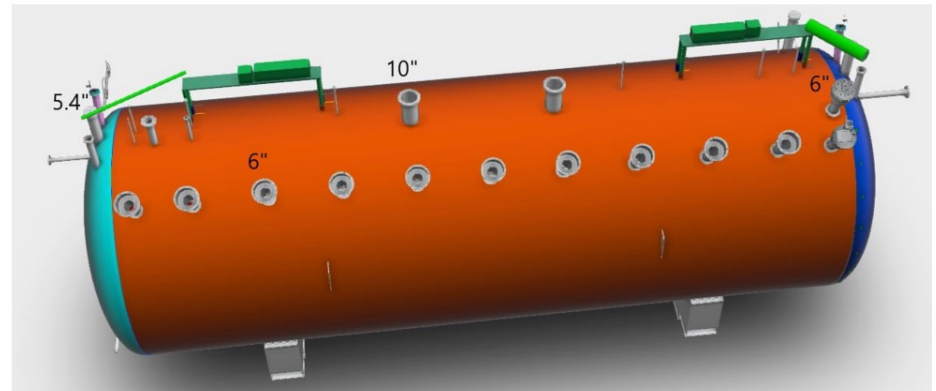
- MicroBooNE is a LArTPC at Fermilab next to MiniBooNE.
- Its main physics goal is to determine whether the observed MiniBooNE excess is electron-like or photon-like in the BNB.
- Also collected neutrino data from the second neutrino beam at Fermilab -> access to *higher* energy neutrinos
- It ran from **2015 to 2021** (neutrino beams + R&D campaigns).



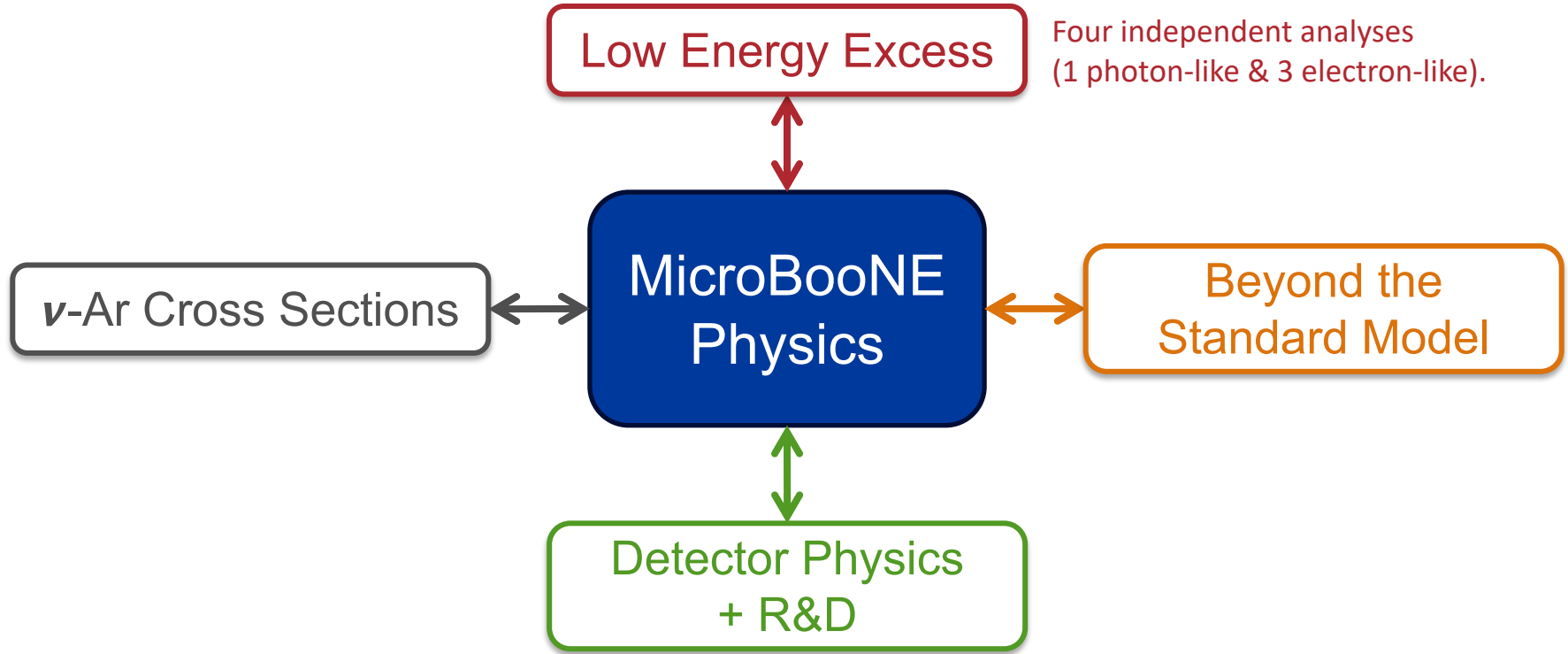
MicroBooNE Decommissioning Effort



- Earlier this year, the MicroBooNE detector entered a decommissioning phase.
 - This will allow us to characterize the detector after 7 years of operation.
 - Potential to understand some of the unresolved mysteries.
- Before venting the cryostat, we took some argon samples that are currently being analyzed through different characterization techniques (e.g. GC/MS).
- The cryostat is now back at ambient temperature, and we are planning to open ports to have a look at the TPC.
- Plans are still brewing, but we want to look at the wire planes and our light detection system:
 - Trying to determine what 7 years in LAr has done to them.



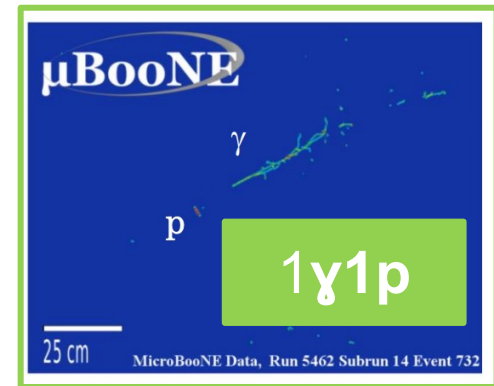
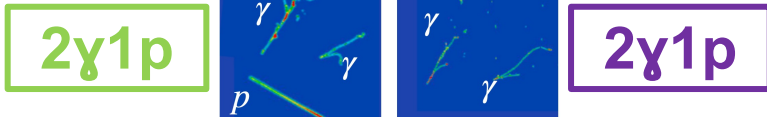
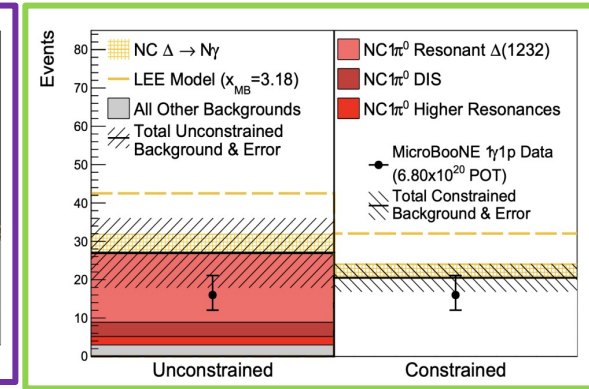
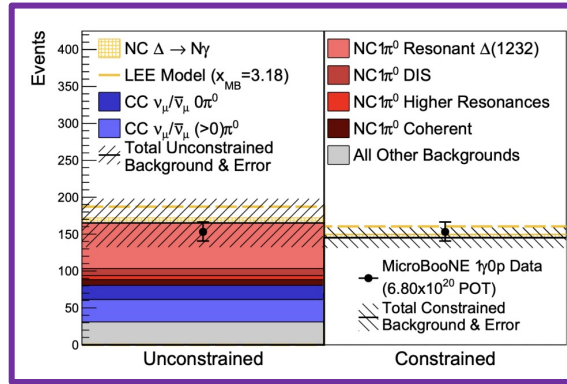
MicroBooNE's Physics Program – Main Outputs



Low Energy Excess Searches – Photons (γ)

[Phys. Rev. Lett. 128, 111801 \(2022\)](#)

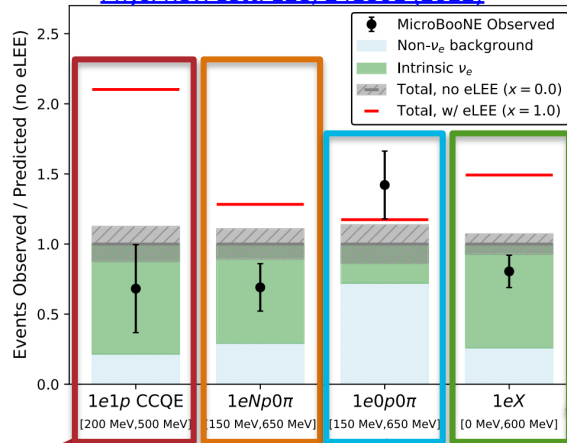
- $NC\Delta \rightarrow N\gamma$ is an important background to MiniBooNE.
 - Can mimic electron-like events
- Two topologies were looked at:
 - $NCA \rightarrow 1\gamma + 0p$
 - $NCA \rightarrow 1\gamma + 1p$
- $NC1\pi^0 \rightarrow 2\gamma$ “side bands” constrained the 1γ channels.



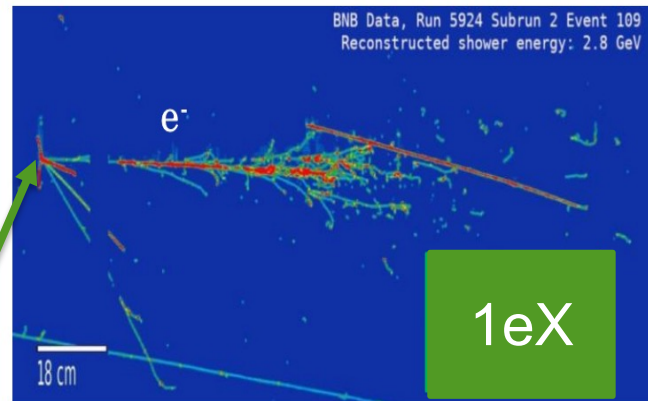
- Photons from $NCA \rightarrow N\gamma$ solely explaining the LEE are **ruled out at the 94.8% CL.**

Low Energy Excess Searches – Electrons (e^-)

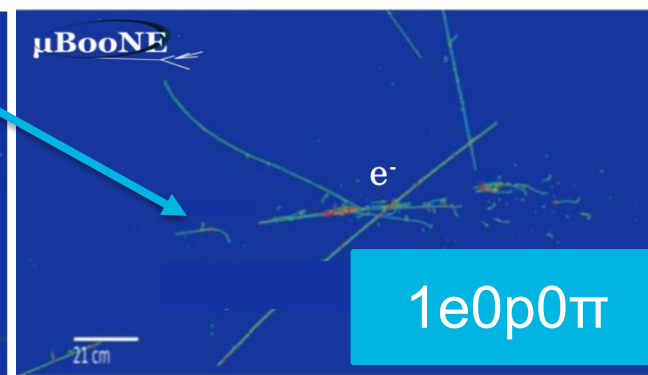
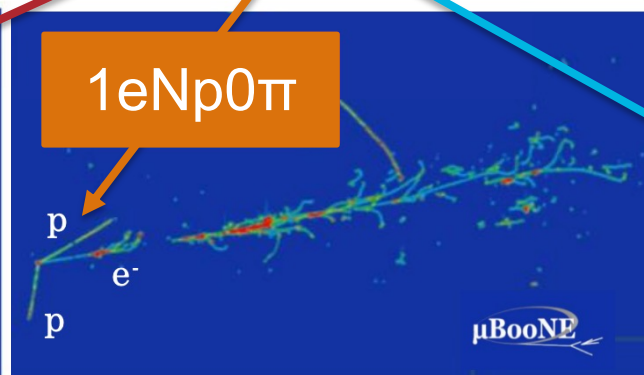
[Phys. Rev. Lett. 128, 241801 \(2022\)](#)



[Phys. Rev. D 105, 112005 \(2022\)](#)



- Three independent analyses for different topologies.
- Currently, there is **no low energy excess observed** in 1e1p, 1eNp, 1eX:
 - ν_e excess rejected at **> 97% CL** as sole explanation for LEE.

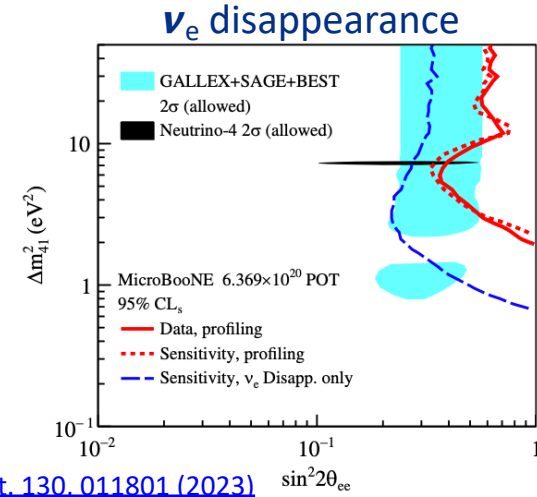
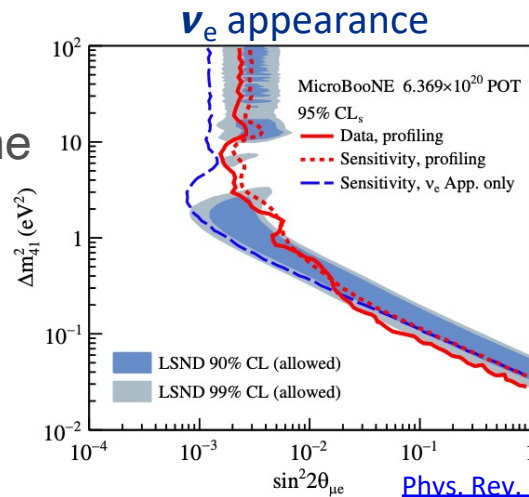
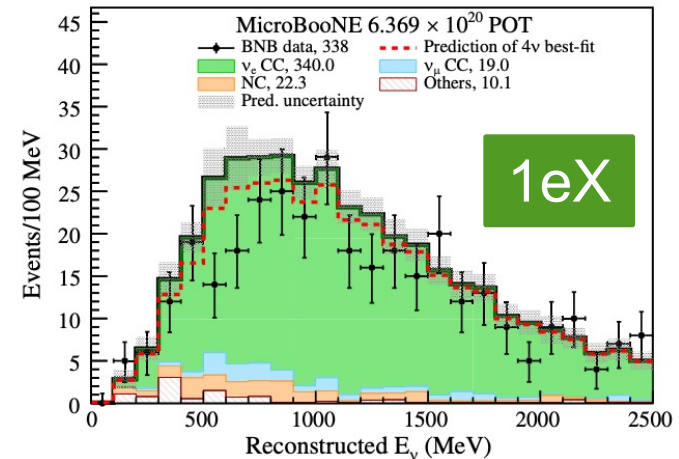


[Phys. Rev. D 105, 112003 \(2022\)](#)

[Phys. Rev. D 105, 112004 \(2022\)](#)

Sterile Neutrinos – (3+1) ν Interpretation

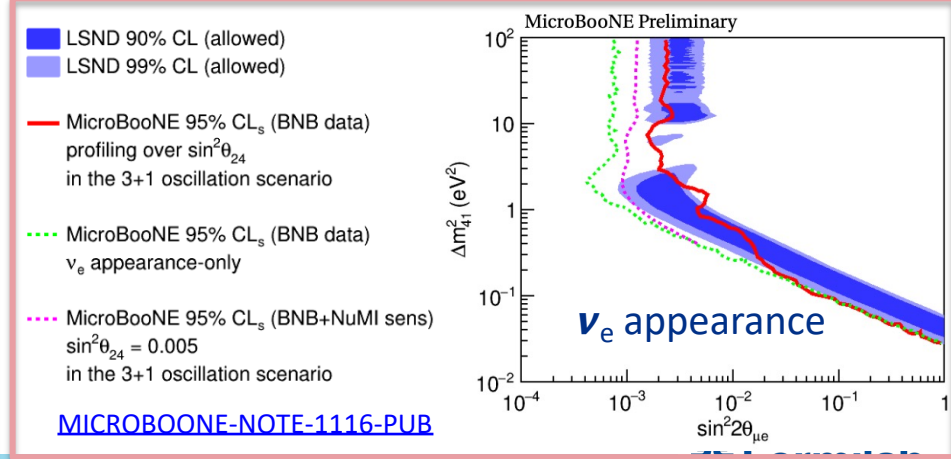
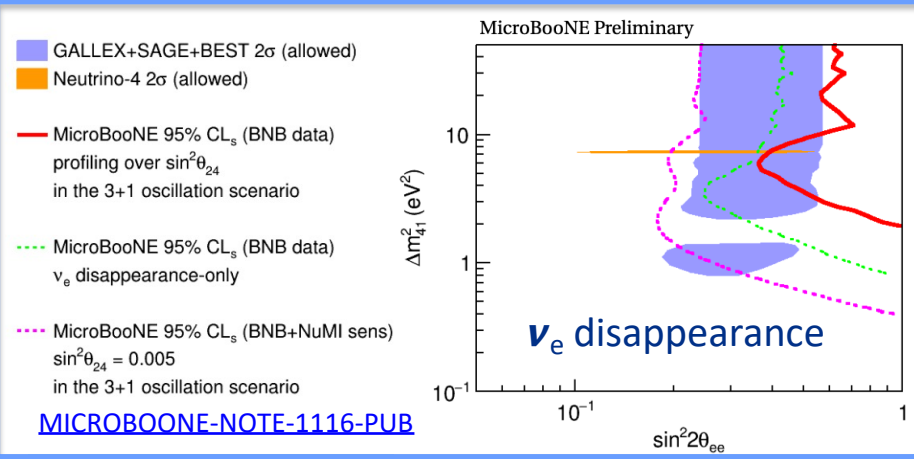
- Taking the **1eX** (inclusive) electron-LEE results, we can reinterpret it with a **sterile neutrino oscillation** hypothesis using only MicroBooNE.
- Here we consider both ν_e appearance and ν_e/ν_μ disappearance effects at the same time.
- The results **agree with the 3ν hypothesis within 1σ** .
- Excludes significant regions of the LSND allowed regions giving the ν_e appearance.
- Excludes regions in the gallium experiments giving ν_e disappearance.



[Phys. Rev. Lett. 130, 011801 \(2023\)](#)

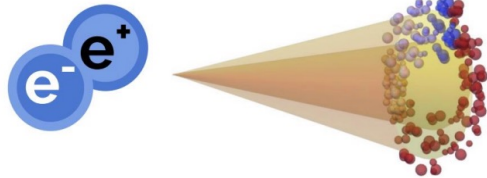
Sterile Neutrinos – (3+1) ν Interpretation with **BNB & NuMI**

- When $\sin^2 \theta_{24}$ approaches the BNB intrinsic ratio of $\nu_e / \nu_\mu \rightarrow$ sensitivity degrades.
 - ν_e disappearance can cancel out ν_e appearance.
- Since BNB and NuMI beams have different ratios of $\nu_e / \nu_\mu \rightarrow$ degeneracy between the oscillation parameters can be broken.
 - **Improves the sensitivity by a factor of 2!** (dashed magenta vs solid red).
- Full data results will be out soon!

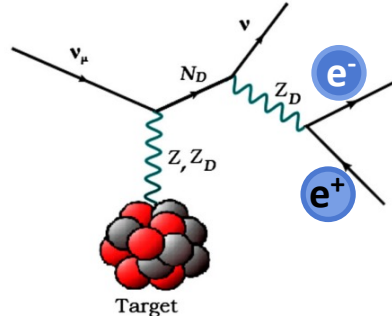


If not γ or e^- , what else could it be? BSM explanations?

- Several BSM models could explain the MiniBooNE LEE.
 - Beyond light sterile neutrinos -> new particles, new scalars, dark matter, etc...
- Many of them rely on the production of an e^+e^- pair.
 - This could mimic a single photon-like event depending on kinematics and process!
- MicroBooNE is currently probing some of these models.
- Results are expected soon!



HNL Upscattering

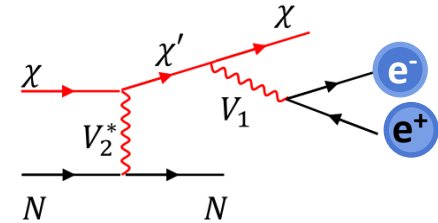


[Phys. Rev. Lett. 121 24, 241801 \(2018\)](#)

[Phys. Rev. D 99 071701 \(2019\)](#)

[Phys. Lett. B 820 136531 \(2021\)](#)

Dark Matter Upscattering



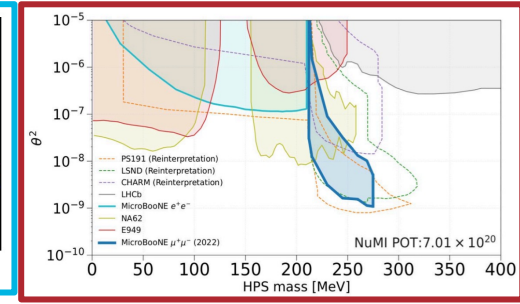
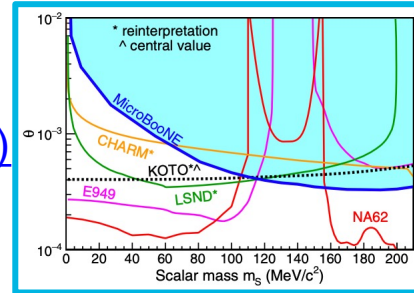
[Phys. Rev. Lett. 129 11, 111803 \(2022\)](#)

Other BSM Searches in MicroBooNE



- **Higgs Portal Scalars (HPS):**

- $e^+e^- \rightarrow$ [Phys. Rev. Lett. 127, 151803 \(2021\)](#)
- $\mu^+\mu^- \rightarrow$ [Phys. Rev. D 106 9, 092006 \(2022\)](#)



- **Heavy Neutral Lepton (HNL):**

- $\mu^+\pi^-$ or $\mu^-\pi^+$ (Majorana) & $\mu^-\pi^+$ (Dirac) in BNB \rightarrow [Phys. Rev. D 101, 052001 \(2020\)](#)
- $\mu^+\mu^-$ & $\mu\pi$ in NuMI \rightarrow [Phys. Rev. D 106 9, 092006 \(2022\)](#)
- e^+e^- & $\pi^0 \rightarrow$ [2310.07660 \[hep-ex\]](#) (accepted by PRL ~2 weeks ago!)

New Results!

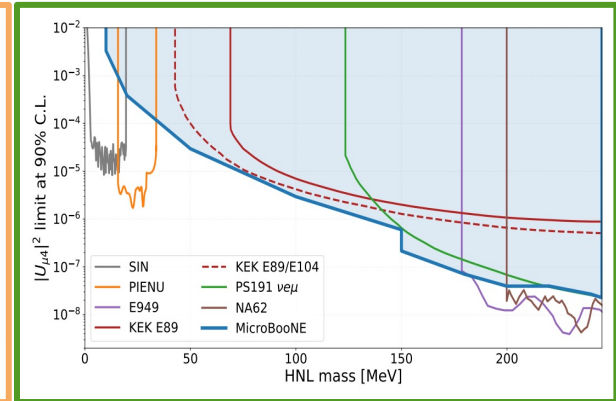
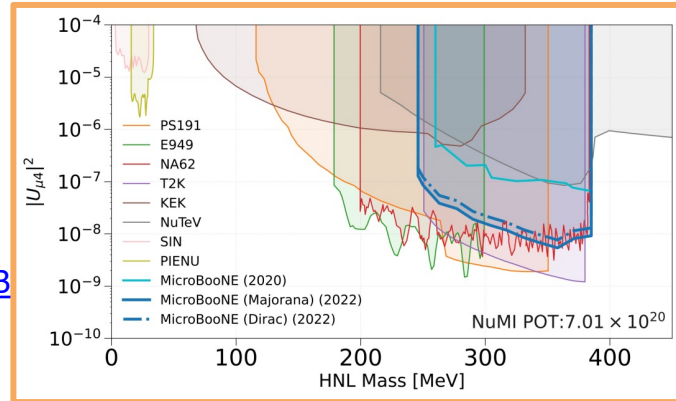
- **Neutron-antineutron oscillation**

- [2308.03924 \[hep-ex\]](#)

- **Dark tridents**

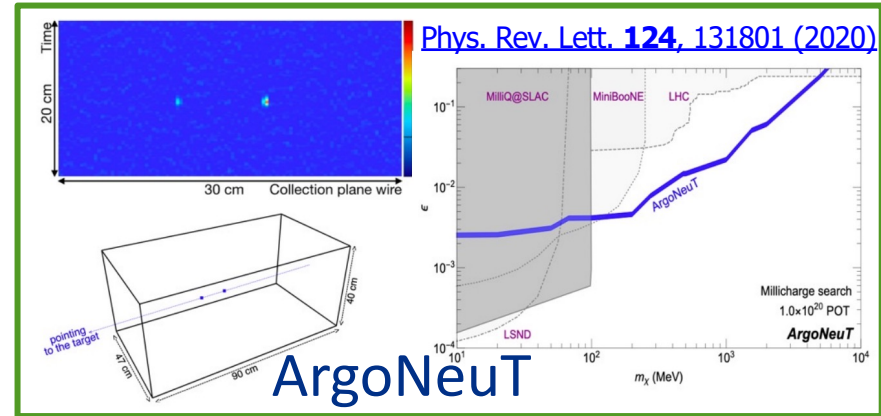
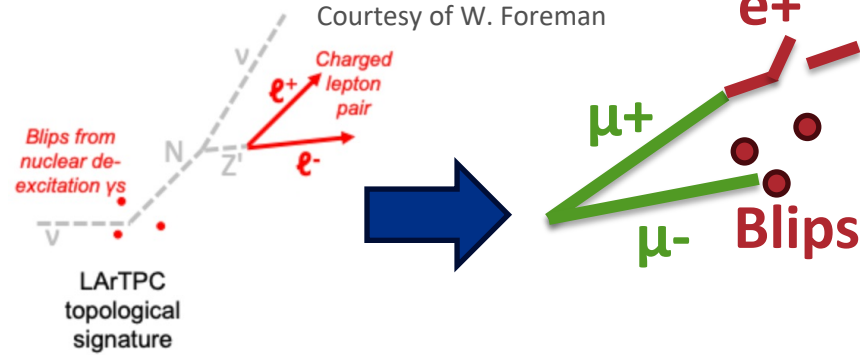
- [MICROBOONE-NOTE-1118-PUB](#)

- **Millicharged particles**



MeV-Scale Physics – What can it be used for?

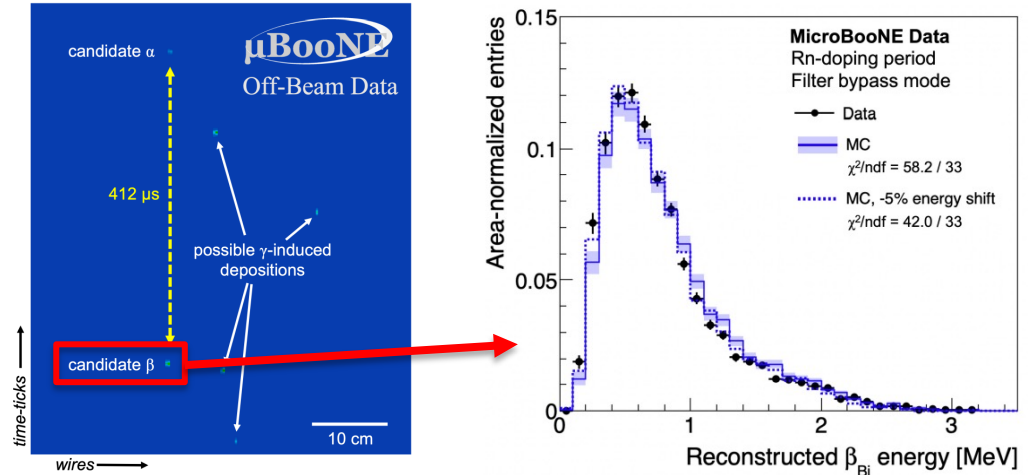
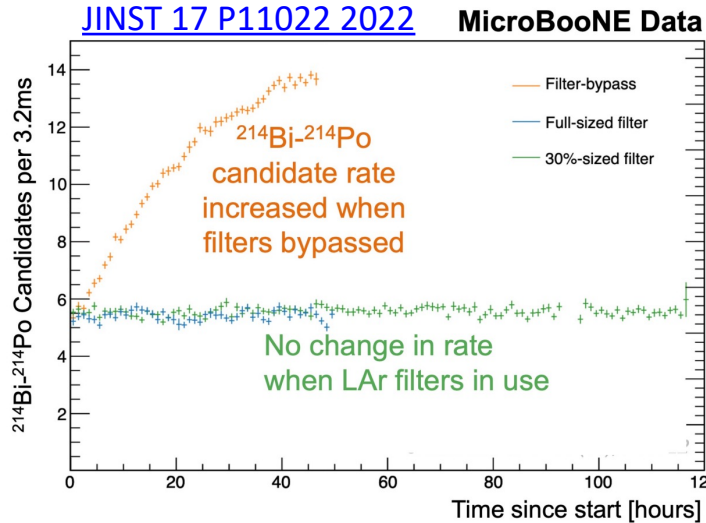
- LArTPCs events include MeV-Scale blips that can come from hadronic interactions.
- Identifying specific particle topological features and improve background rejection could improve sensitivity to some BSM signatures
 - Potential in charge-sign discrimination for $\mu+/-$ & $\pi+/-$
- Can we do any physics or test our ability to reconstruct these blips? Yes!
- ArgoNeuT pioneered with looking at blips at the end of muon tracks and millicharged particle interactions in the TPC.



MeV-Scale Physics with MicroBooNE – Radon Search



arXiv:2307.03102 (under PRD review)



- MicroBooNE expanded on ArgoNeuT’s “MeV-blip” reconstruction algorithm used for millicharged particles search.
- We **injected Rn** during the R&D campaign to look for **Bi(β) -Po (α) signatures**.
- Had to bypass our extremely good filters!
- Measured the ambient radon through Bi(β)-Po (α).
 - Good β -spectrum reconstruction - These are **very low energy events** for LArTPCs! (“MeV-blips”).
- Measured an ambient radon rate of **0.38 mBQ/kg** at a 95% CL upper limit outside of the Rn-doping period.
- DUNE Rn requirement: < 1 mBQ/kg.



MicroBooNE Extensive Cross Section Program



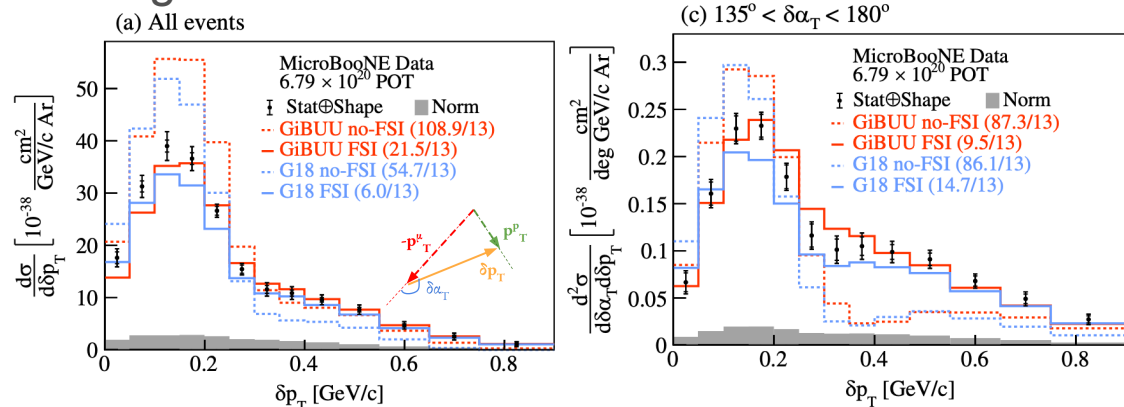
- We have **15 publications** and **~30 active analyses** ν -argon cross section including rare/exclusive channels with BNB and NuMI beams!
- Most recent publication is on **Transverse Kinetic Imbalance** both single & double differential results!

Rare channels

- Λ production @ NuMI
[Phys. Rev. Lett. 130, 231802 \(2023\)](#)
- η production @ BNB
[arXiv:2305.16249](#), submitted to PRL
- CC0 π**
 - 1D νe CCNp0 π @ BNB
[Phys. Rev. D 106, L051102 \(2022\)](#)
 - 1D & 2D $\nu\mu$ CC1p0 π Kinematic Imbalance @ BNB
[Phys. Rev. Lett. 131, 101802 \(2023\)](#)
[Phys. Rev. D 108, 053002 \(2023\)](#)
[arxiv:2310.06082](#), submitted to PRD
 - 1D $\nu\mu$ CC1p0 π @ BNB
[Phys. Rev. Lett. 125, 201803 \(2020\)](#)
 - 1D $\nu\mu$ CC2p @ BNB
[arXiv:2211.03734](#)
 - 1D $\nu\mu$ CCNp0 π @ BNB
[Phys. Rev. D102, 112013 \(2020\)](#)

- CC Inclusive**
 - 1D & 2D $\nu\mu$ CC inclusive @ BNB
[Phys. Rev. Lett. 123, 131801 \(2019\)](#)
 - 1D $\nu\mu$ CC Ev @ BNB
[Phys. Rev. Lett. 128, 151801 \(2022\)](#)
 - 3D CC Ev @ BNB
[arXiv:2307.06413](#), submitted to PRL
 - 1D ve CC inclusive @ NuMI
[Phys. Rev. D105, L051102 \(2022\)](#)
[Phys. Rev. D104, 052002 \(2021\)](#)
- Pion production**
 - 3D CC Ev @ BNB
[arXiv:2307.06413](#), submitted to PRL
 - $\nu\mu$ NC π 0 @ BNB
[Phys. Rev. D 107, 012004 \(2023\)](#)

- CC inclusive**
 - $\nu\mu$ CC inclusive @ NuMI
 - ve / $\nu\mu$ ratios @ BNB, NuMI
 - 3D Ev, E_{μ} , hadronic energy @ NuMI & BNB
 - ve @ NuMI
- Pion production**
 - $\nu\mu$ CC1 π + @ BNB, NuMI
 - $\nu\mu$ CCN π @ NuMI
 - 1D $\nu\mu$ CC π 0 @ BNB
 - 2D $\nu\mu$ CC/NC π 0 @ BNB
 - 2D ve, μ NC π 0 @ BNB
 - Kinematic imbalance
- CC0 π**
 - $\nu\mu$ CC0 π inclusive @ BNB
 - 2D $\nu\mu$ CCNp0 π @ BNB
 - 1D ve CC0 π Np @ NuMI
 - 1D $\nu\mu$ NC1p0 π @ BNB
- Rare & novel channels**
 - $\nu\mu$ CC kaon @ BNB, NuMI
 - MeV-scale physics
 - Neutrons @ BNB



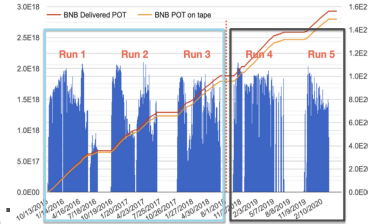
[Phys. Rev. Lett. 131, 101802 \(2023\)](#) [Phys. Rev. D 108, 053002 \(2023\)](#)



Summary



- MicroBooNE completed **7 years of data running** in 2021.
 - Record for the longest running LArTPC in a neutrino beam to date!
 - We currently are in a decommissioning phase to understand certain features observed during operation & look at the longevity of LArTPCs after 7 years.
 - *Rare* and exciting opportunity to inform the greater community!
- We are preparing for **full dataset results** release in the new year:
 - Continuation of previous LEE results through both electrons and photons:
 - **Currently ruling out the MiniBooNE energy excess solely from electrons at the 97% CL and photons from NCA \rightarrow N_γ at 94.8% CL.**
 - Coherent + inclusive photon searches are underway as alternative to NCA.
 - Looking into 3+1 models, and e+e- production as a BSM explanation to LEE.
 - New data-rich results will be released in many cross section channels and BSM.
 - New detector physics measurements + R&D studies already being published.
- 62 publications, more soon!



Questions?



Backup

MicroBooNE Publication Summary



2017 2018 2019 2020 2021 2022 2023

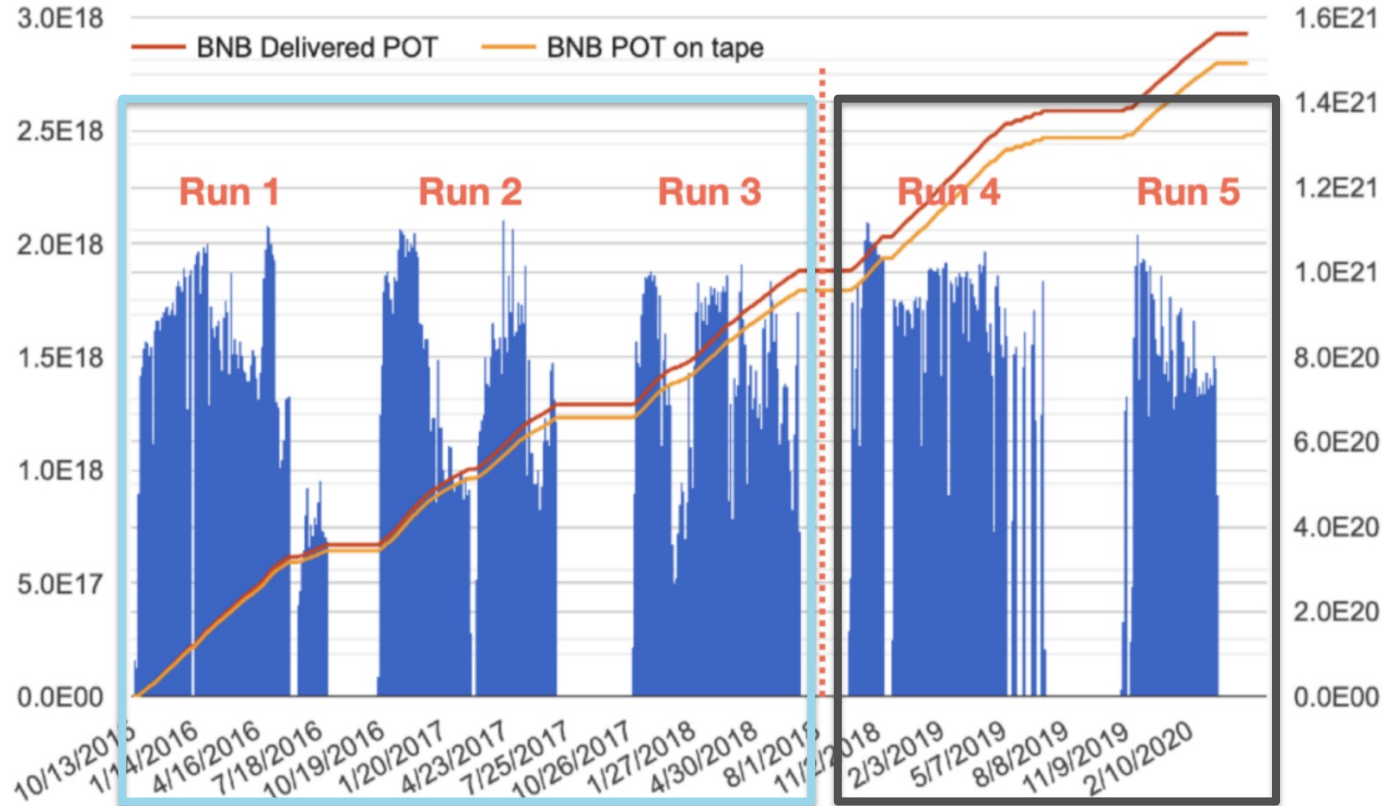
<https://microboone.fnal.gov/documents-publications/>

~62 papers... so far!
Many more in
preparation!

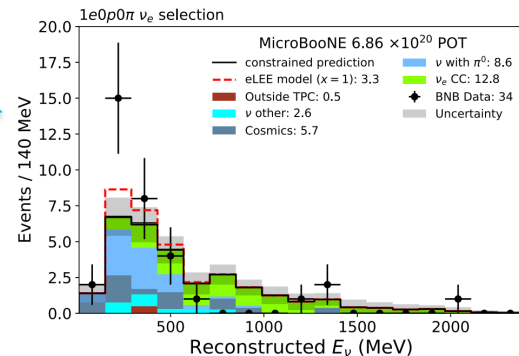
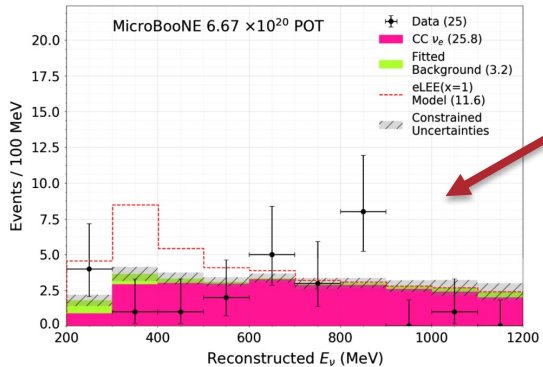
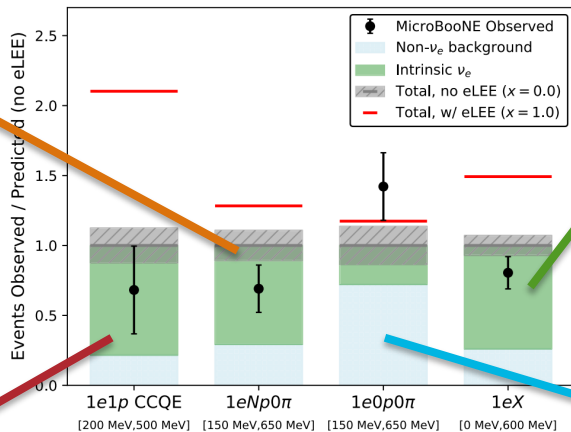
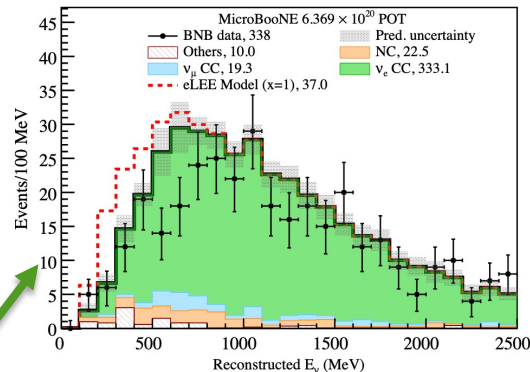
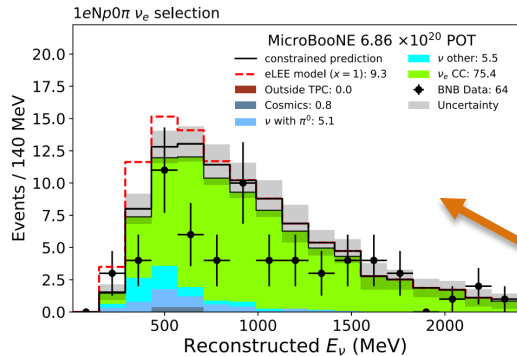
- Search for heavy neutral leptons in electron-positron and neutral-pion final states with the MicroBooNE detector
- Measurement of nuclear effects in neutrino-argon interactions using generalised kinetic imbalance variables with the MicroBooNE detector
- First demonstration for a LAr-TPC-based search for intranuclear neutron-antineutron transitions and annihilation in ^{40}Ar using the MicroBooNE detector
- Measurement of triple-differential inclusive muon-neutrino charged-current cross section on argon with the MicroBooNE detector
- Measurement of ambient radon daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector
- First measurement of η production in neutrino interactions on argon with MicroBooNE
- First demonstration of $\mathcal{O}(1\text{ ns})$ timing resolution in the MicroBooNE liquid argon time projection chamber
- Multi-differential cross section measurements of muon-neutrino argon quasi-elastic-like reactions with the MicroBooNE detector
- First double-differential measurement of kinematic imbalance in neutrino interactions with the MicroBooNE detector
- First measurement of quasi-elastic Λ baryon production in muon antineutrino interactions in the MicroBooNE detector
- First measurement of differential cross sections for muon neutrino charged current interactions on argon with a two-proton final state in the MicroBooNE detector
- First constraints on light sterile neutrino oscillations from combined appearance and disappearance searches with the MicroBooNE detector
- Differential cross section measurements of charged current ν_e interactions without final-state pions in MicroBooNE
- Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector
- Measurement of neutral current single π^0 production on argon with the MicroBooNE detector
- Observation of radon mitigation for the MicroBooNE by a liquid argon filtration system
- Cosmic ray muon clustering for the MicroBooNE liquid argon time projection chamber using sMask-RCNN
- Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data
- First measurement of energy-dependent inclusive muon neutrino charged-current cross sections on argon with the MicroBooNE detector
- Search for an anomalous excess of inclusive charged-current ν_e interactions without pions in the final state with the MicroBooNE experiment
- Search for an anomalous excess of charged-current quasi-elastic ν_e interactions with the MicroBooNE experiment using deep-learning-based reconstruction
- New theory-driven GENIE tune for MicroBooNE
- Search for an anomalous excess of inclusive charged-current ν_e interactions in the MicroBooNE experiment using Wire-Cell reconstruction
- Search for an excess of electron neutrino interactions in MicroBooNE using multiple final state topologies
- Wire-Cell 3D pattern recognition techniques for neutrino event reconstruction in large LArTPCs
- Electromagnetic shower reconstruction and energy validation with Michel electrons and π^0 samples for the deep-learning-based analyses in MicroBooNE
- Search for neutrino-induced NC Δ radiative decay in MicroBooNE and a first test of the MiniBooNE low-energy excess under a single-photon hypothesis
- First measurement of inclusive electron-neutrino and antineutrino charged current differential cross sections in charged lepton energy on argon in MicroBooNE
- Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data
- Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
- Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
- Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
- Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
- Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
- Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
- High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
- Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
- A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
- Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
- The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
- Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
- Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
- First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
- Search for heavy neutral leptons decaying into muon pairs in the MicroBooNE detector
- Reconstruction and Measurement of $\mathcal{O}(100)$ MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
- A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
- Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
- First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~ 0.8 GeV with the MicroBooNE Detector
- Design and Construction of the MicroBooNE Cosmic Ray Tagger System
- Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
- First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
- A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
- Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
- Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
- Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
- The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
- Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
- Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
- Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
- Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
- Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
- Design and Construction of the MicroBooNE Detector

Running over 5 years of Beam Data!

- All analyses published so far only use ~1/2 of the full dataset.
- Expect to have full dataset analyses start to come out in 2024!



Low Energy Excess Searches Through Electrons

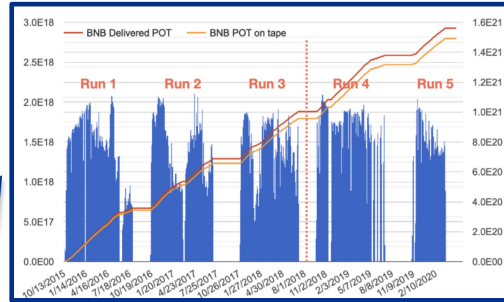


MicroBooNE Timeline

Construction + Installation

Operations

Low energy
excess
anomalies



```

uboonedaq@ubdaq-prod-ervb:~$
File Edit View Search Terminal Help
ENTER [stop] TO STOP THE RUN:
Current (Run, Subrun) is (28819, 264). We've been running 47.57 minutes.

ENTER [stop] TO STOP THE RUN:
stop
Sending StopRunRequest to "allElements" target in partition 0.
Received StopRunResponse from assemblerAppsvb with status 0 (Success).
Received StopRunResponse from sebAppseb04 with status 0 (Success).
Received StopRunResponse from sebAppseb01 with status 0 (Success).
Received StopRunResponse from sebAppseb07 with status 0 (Success).
Received StopRunResponse from sebAppseb08 with status 0 (Success).
Received StopRunResponse from sebAppseb06 with status 0 (Success).
Received StopRunResponse from sebAppseb10 with status 0 (Success).
Received StopRunResponse from sebAppseb09 with status 0 (Success).
Received StopRunResponse from sebAppseb03 with status 0 (Success).
Received StopRunResponse from sebAppseb02 with status 0 (Success).
Received StopRunResponse from sebAppseb05 with status 0 (Success).
Run Stopped after 48.00 minutes!
    
```

Mid 2015

2007

Late
2015

2020

Late
2021

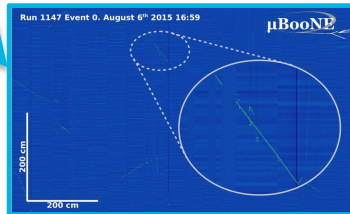
R&D Period

2021

2023

A Proposal for a New Experiment
Using the Booster and NuMI Neutrino Beamlines: MicroBooNE

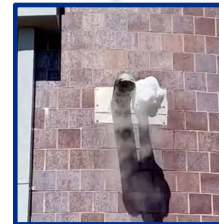
[Link to proposal](#)



Filling + Commissioning



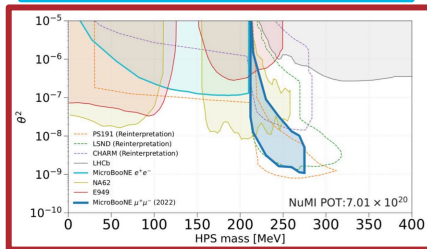
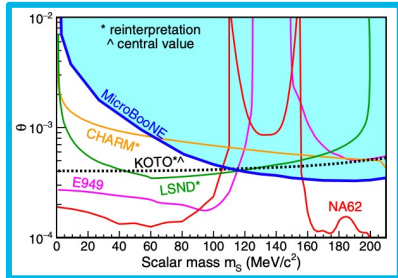
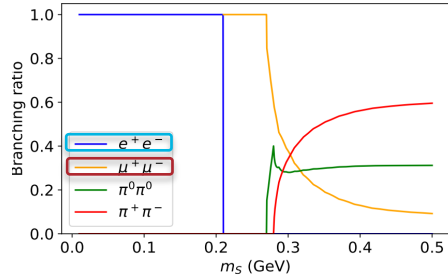
Decommissioning



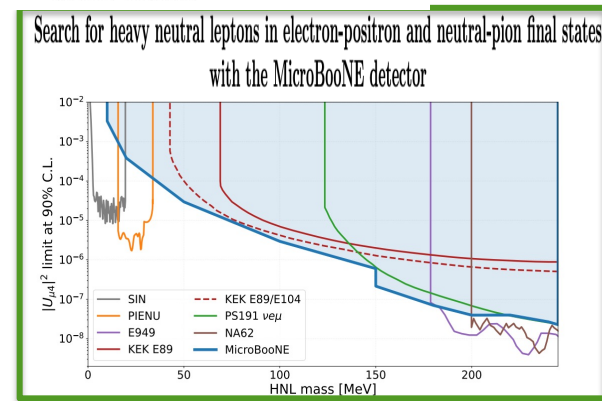
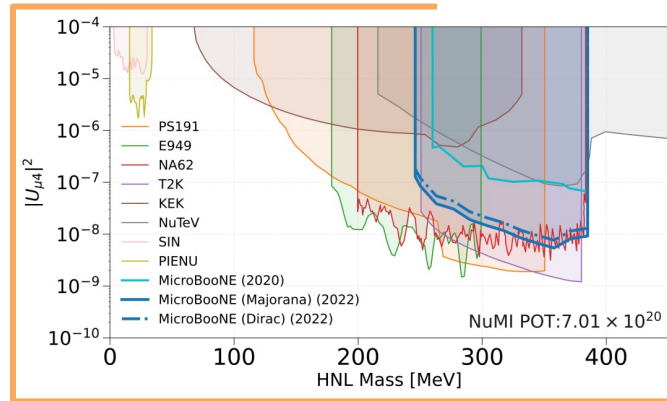
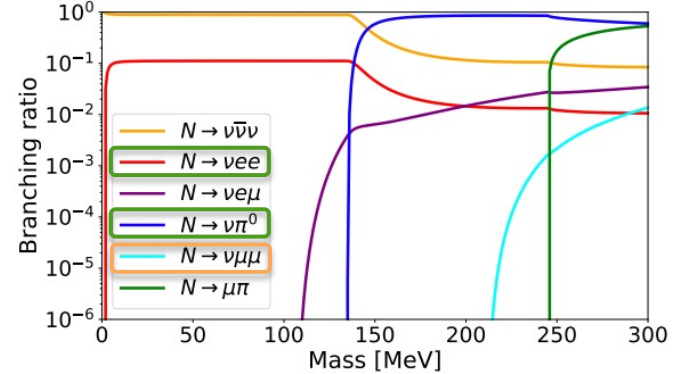
Argon Venting
Fermilab

Other BSM Searches in MicroBooNE

Higgs Portal Scalars (HPS)



Heavy Neutral Lepton (HNL)



First demonstration of $\mathcal{O}(1 \text{ ns})$ timing resolution in the MicroBooNE liquid argon time projection chamber

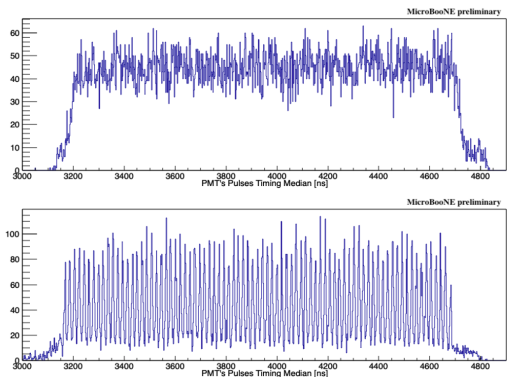


Figure 7: Top: neutrino interaction timing distribution before the reconstruction. Bottom: neutrino interaction timing distribution after the reconstruction. The 81 bunches composing the $\sim 1.6 \mu\text{s}$ beam pulse sub-structure are well visible after the reconstruction.

Run: 16023 Subrun: 61 Event: 3065

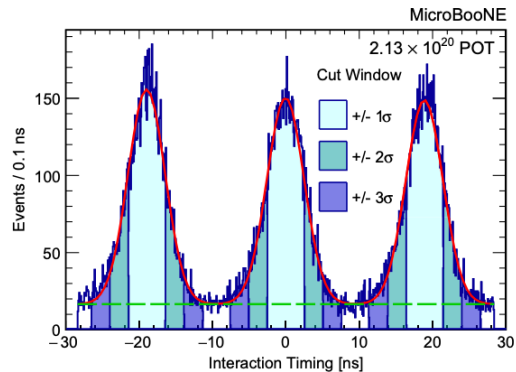
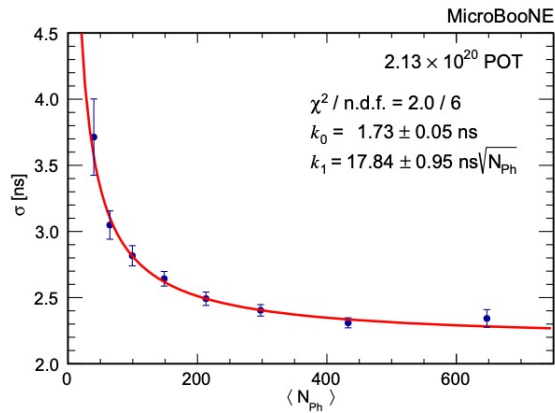
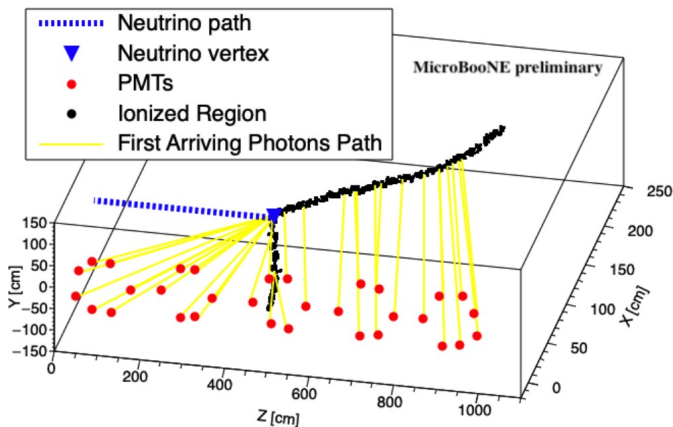
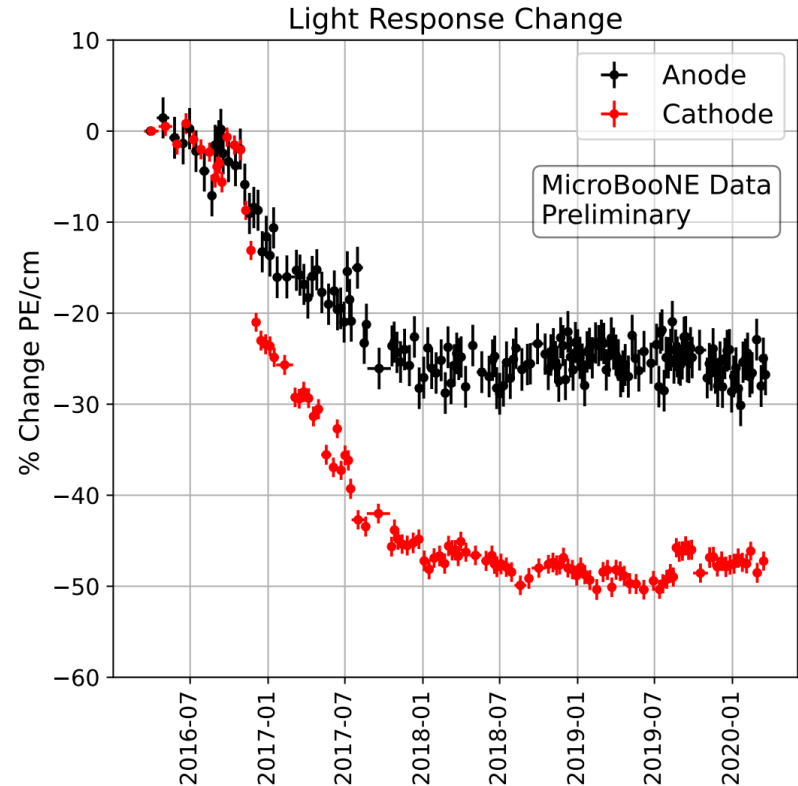


FIG. 12. Interaction timing resolution as a function of the total number of photons detected.

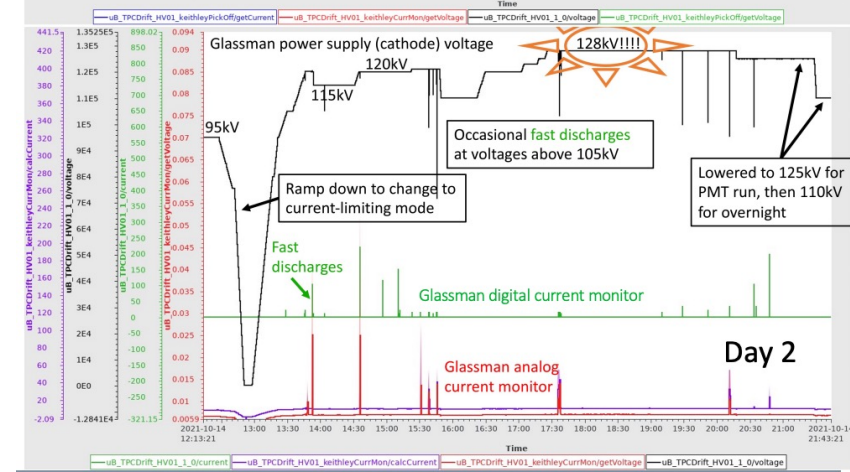
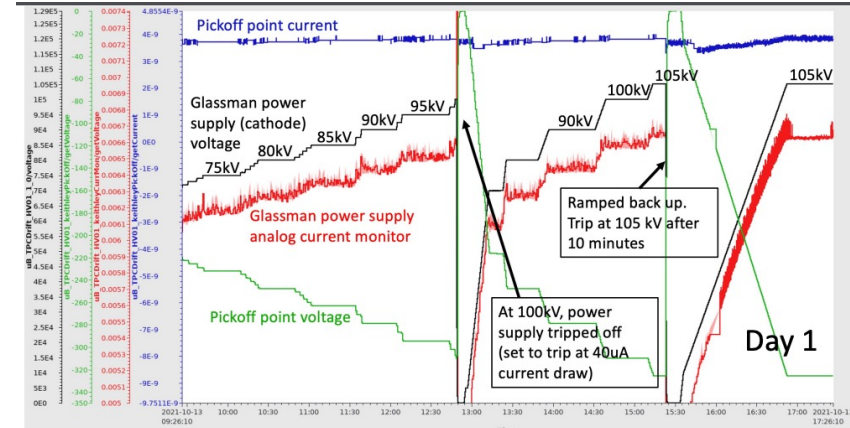
Time-Based Light Yield Stability Measurement – Results

- The truncated median is used to populate the light response change by comparing to the first time bin.
- Here we show the relative change for tracks at the **anode (black)** and **cathode (red)**.
- By mid 2018, the light yield at the cathode is nearly $\frac{1}{2}$ of what it was initially but then stabilizes.
- **Important feature:** the amplitude of the decline is different at the anode compared at the cathode.



Running at Design Voltage 128 kV

- Ramped up to the design voltage during the last R&D runs.
- Record cosmic data at the different voltages for future detector physics measurements that are E-Field dependent.



Impurities in MicroBooNE

- The CIEMAT DM group has kindly analyzed a sample of our argon after a discussion at a previous LiDINE. Thank you Roberto Santorelli!
- They have found that we have *more* nitrogen, krypton and even xenon compared to commercial high purity argon.
- These can quench (late light) and/or absorb the light.
- We do not currently have an absolute value of the concentration but good guesses.

