MicroBooNE – Overview of Recent Results

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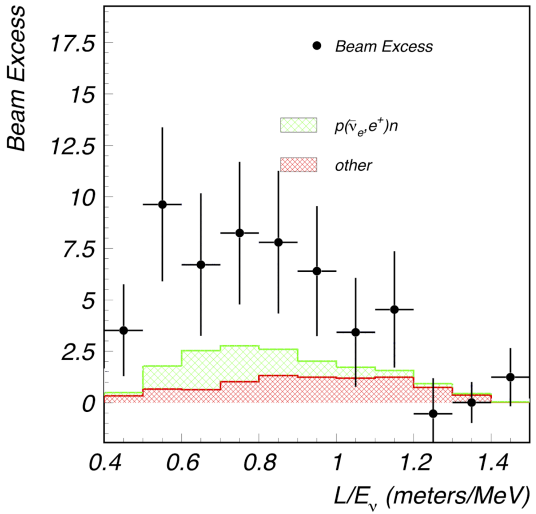
NuPhys 2023 @ King's College London

19/12/2023

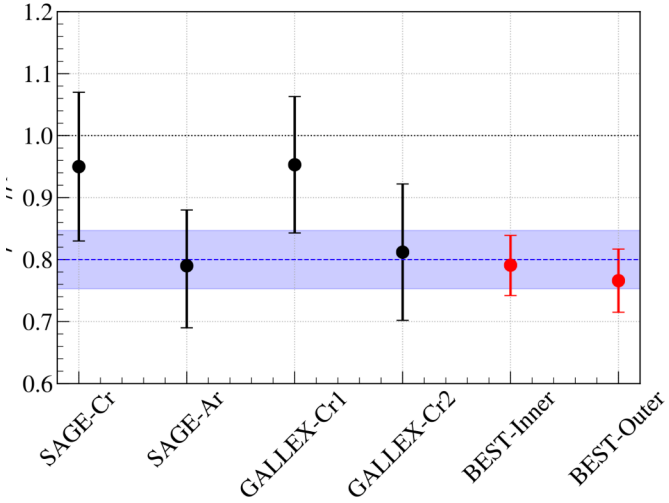
Low Energy Excess (LEE) and You – Anomalies

Phys. Rev. D **64**, 112007 (2001)



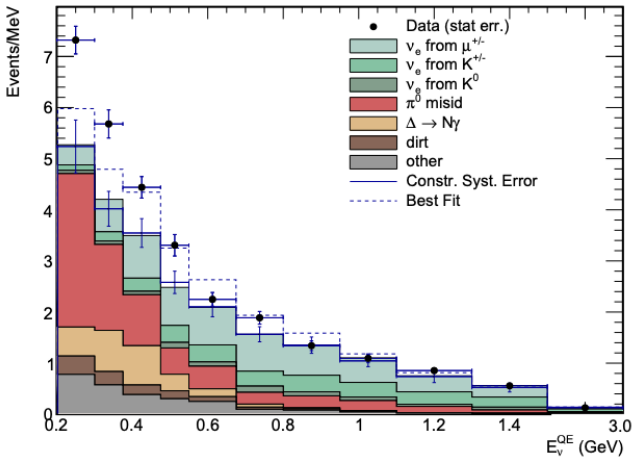
LSND -> stopped pion source. Observed **excess** of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam.

Phys. Rev. C 105 6, 065502 (2022)



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

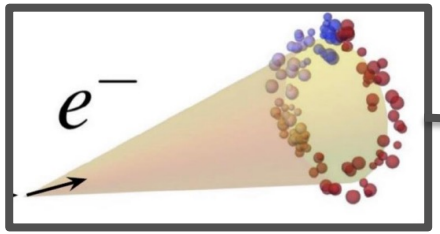
Phys. Rev. D 103, 052002 (2021)



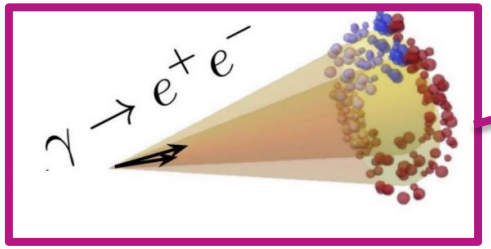
MiniBooNE -> neutrino beam. Observed **excess** of $\nu_e(\bar{\nu}_e)$ in a $\nu_\mu(\bar{\nu}_\mu)$beam.

Low Energy Excess (LEE) and You – MiniBooNE

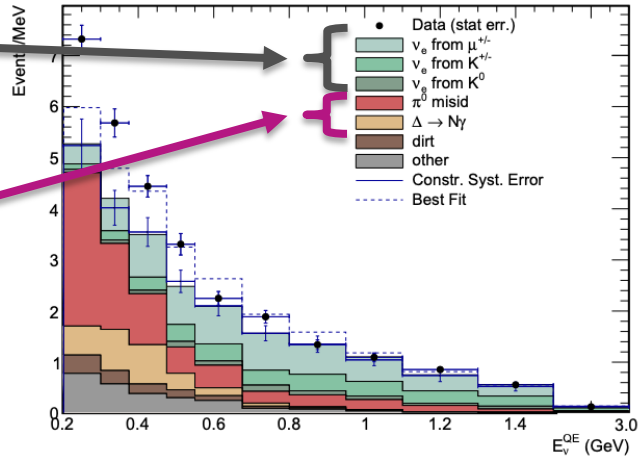
Signal



Background



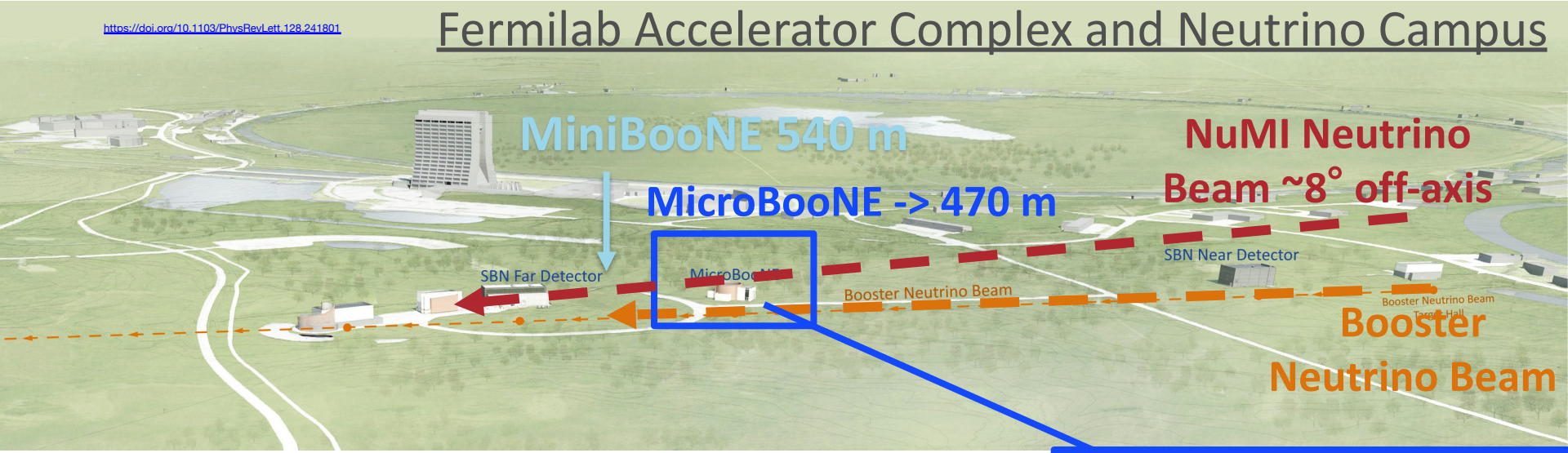
Phys. Rev. D 103, 052002 (2021)



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

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

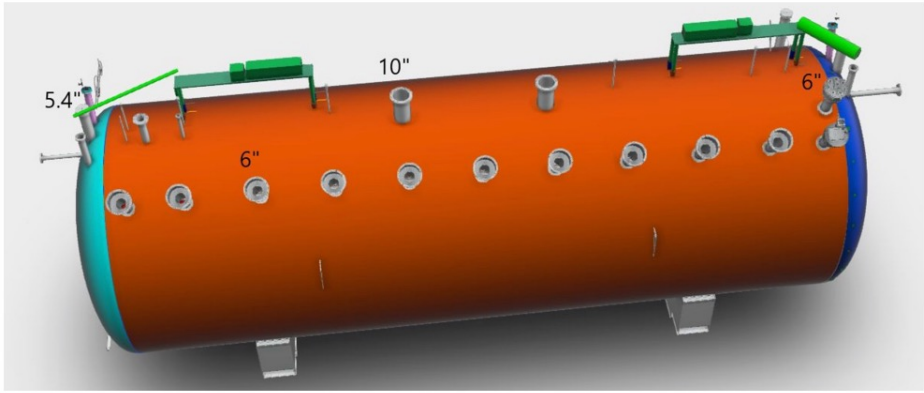
MicroBooNE at Fermilab



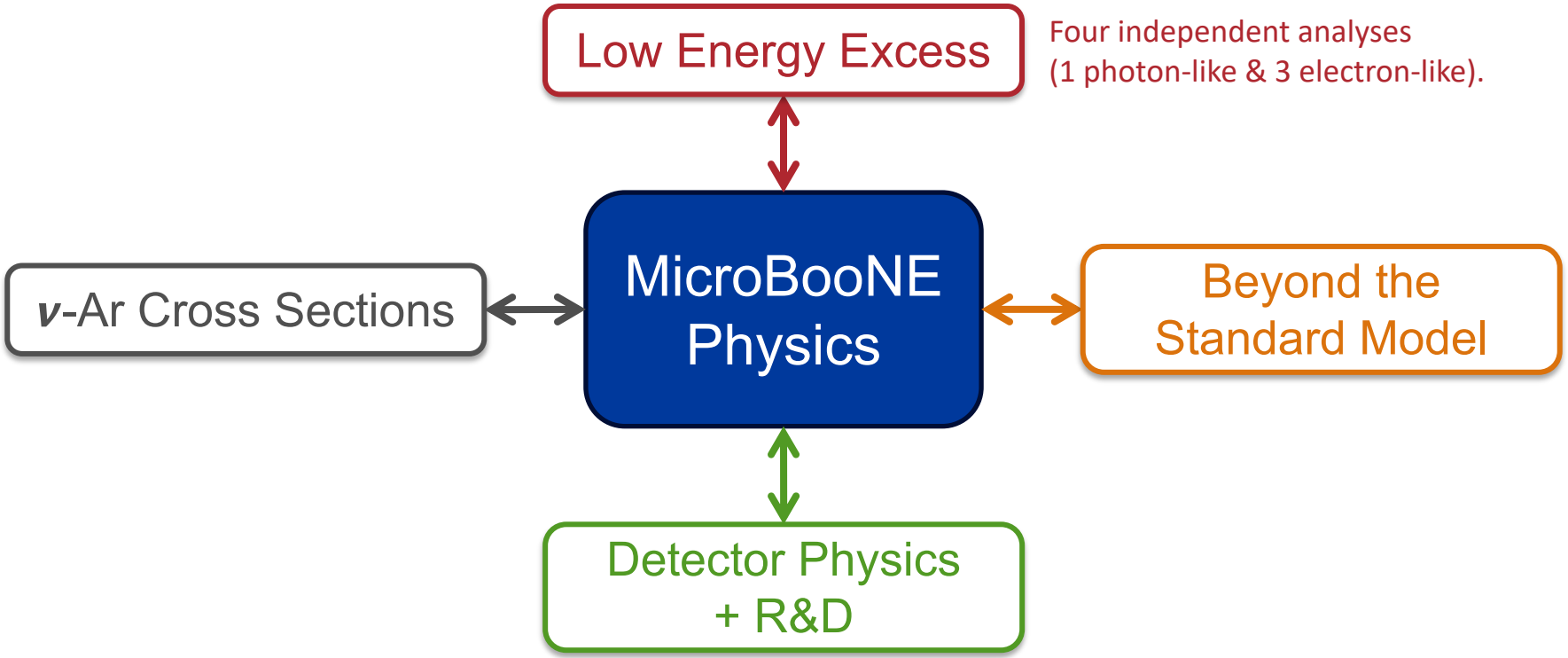
- MicroBooNE is a LArTPC at Fermilab next to MiniBooNE.
- Its main physics goal is to determine whether the observed MiniBooNE excess is electron-like or photon-like in the BNB.
- Also collected neutrino data from the second neutrino beam at Fermilab -> access to *higher* energy neutrinos
- It ran from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



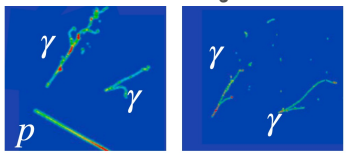
MicroBooNE's Physics Program – Main Outputs



Low Energy Excess Searches – Photons (γ)

- NCΔ → Nγ is an important background to MiniBooNE.
  - Can mimic electron-like events
- Two topologies were looked at:
  - **NCΔ → 1γ + 0p**
  - **NCΔ → 1γ + 1p**
- NC1π0 → 2γ "side bands" constrained the 1γ channels.

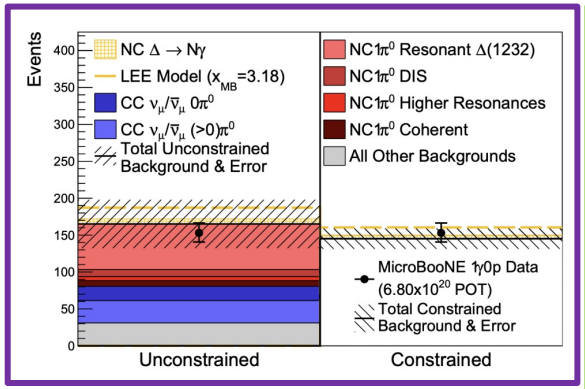
2γ1p

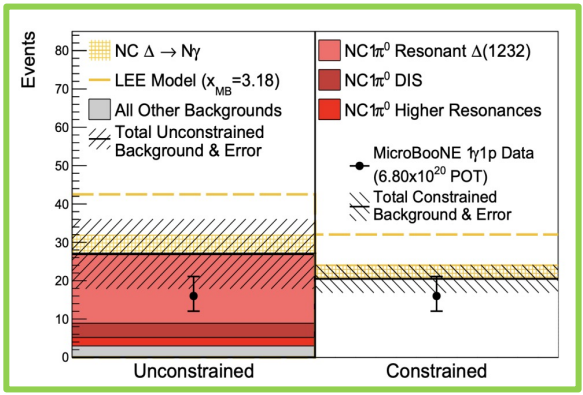


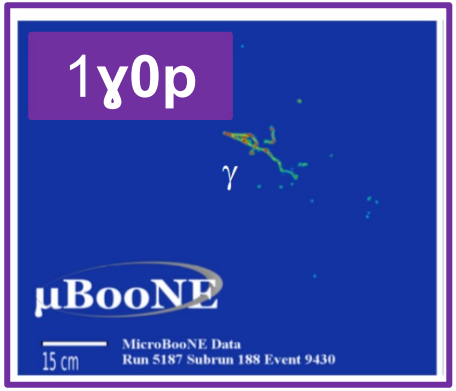
2γ1p

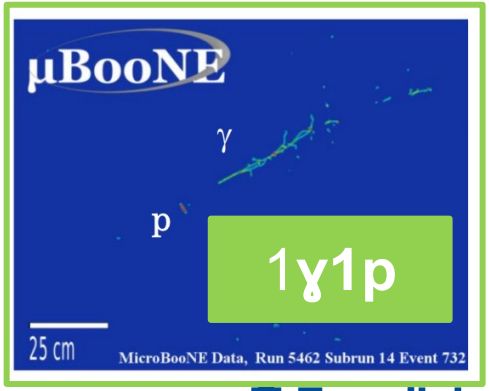
- Photons from NCΔ →Nγ solely explaining the LEE are **ruled out at the 94.8% CL.**

Phys. Rev. Lett. **128**, 111801 (2022)





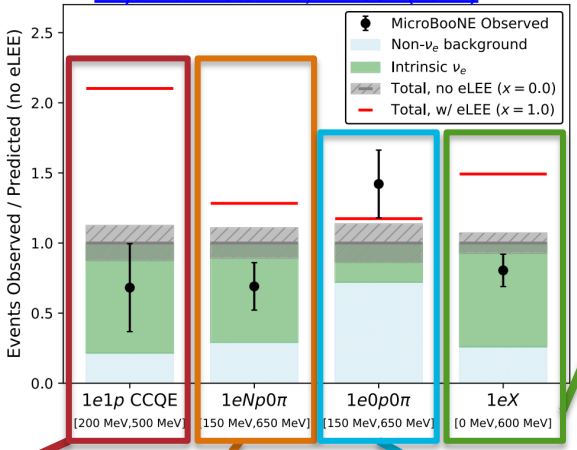




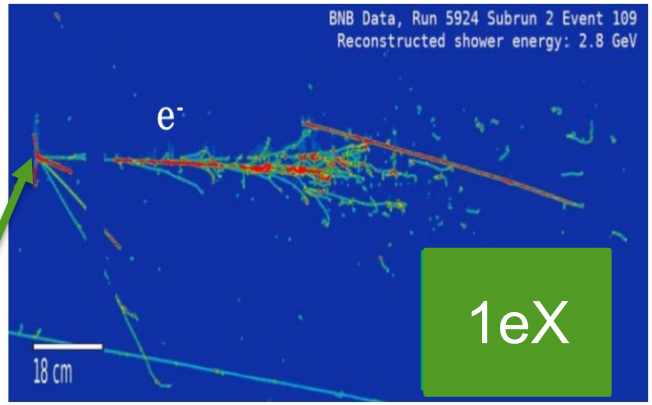
Low Energy Excess Searches – Electrons (e-)

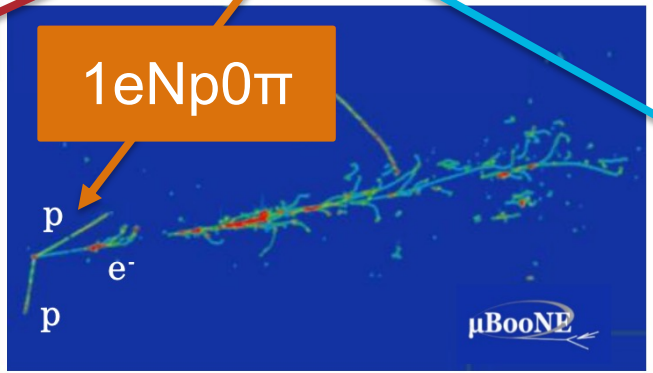
- Three independent analyses for different topologies.
- Currently, there is **no low energy excess observed** in 1e1p, 1eNp, 1eX:
  - **ν_e excess rejected at > 97% CL as sole explanation for LEE.**

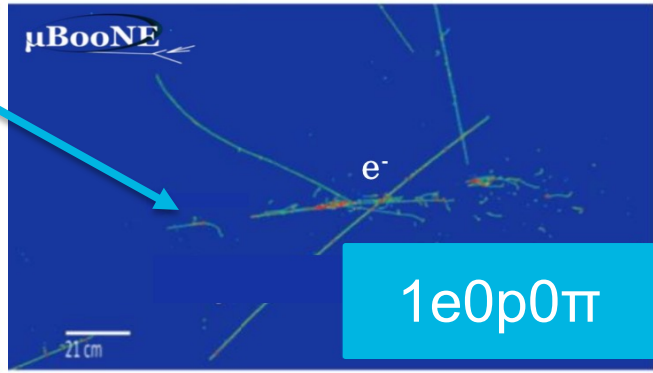
Phys. Rev. Lett. 128, 241801 (2022)



Phys. Rev. D 105, 112005 (2022)





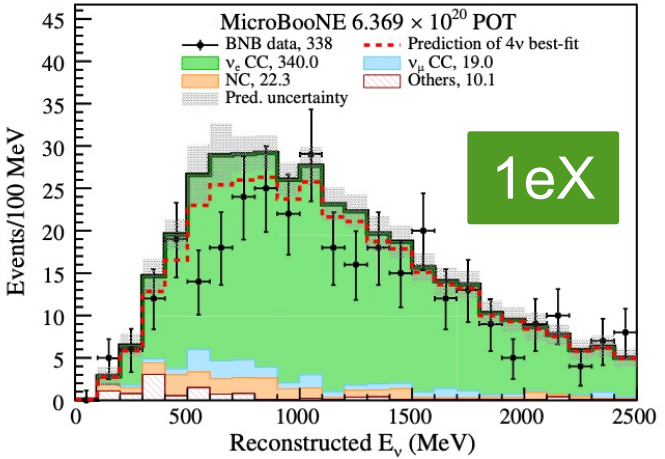


Phys. Rev. D 105, 112003 (2022)

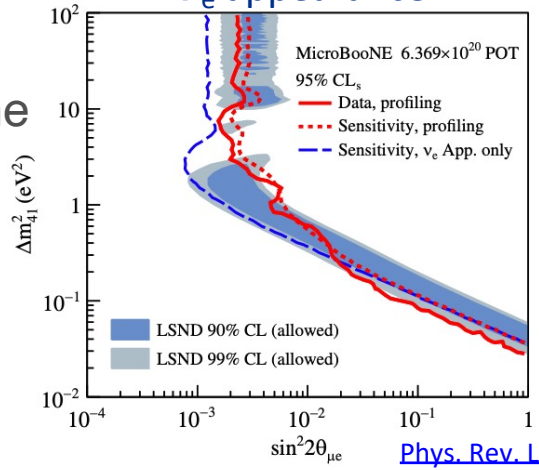
Phys. Rev. D 105, 112004 (2022)

Sterile Neutrinos – (3+1) *ν* Interpretation

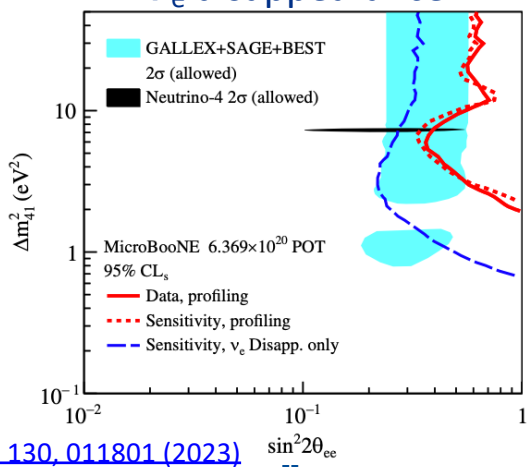
- Taking the **1eX** (inclusive) electron-LEE results, we can reinterpret it with a **sterile neutrino oscillation** hypothesis using only MicroBooNE.
- Here we consider both ν_e appearance and ν_e/ ν_μ disappearance effects at the same time.
- The results **agree with the 3*ν* hypothesis within 1σ**.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



ν_e appearance



ν_e disappearance

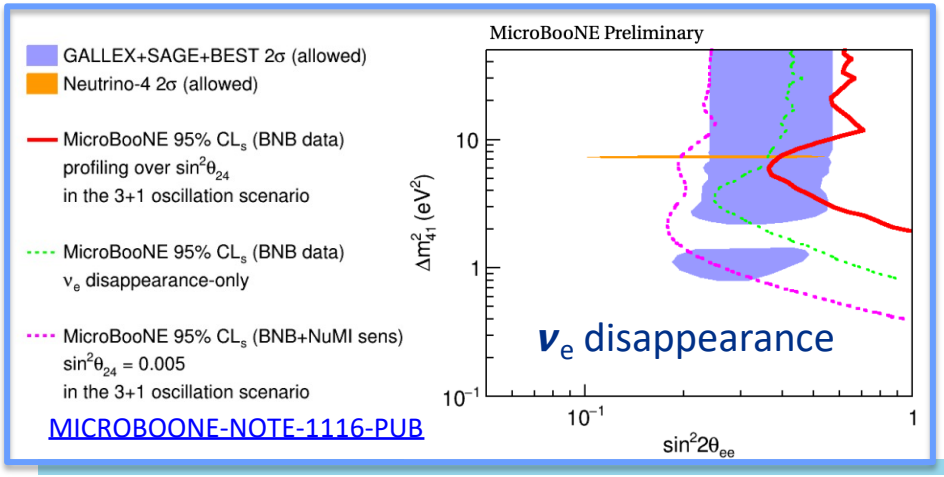


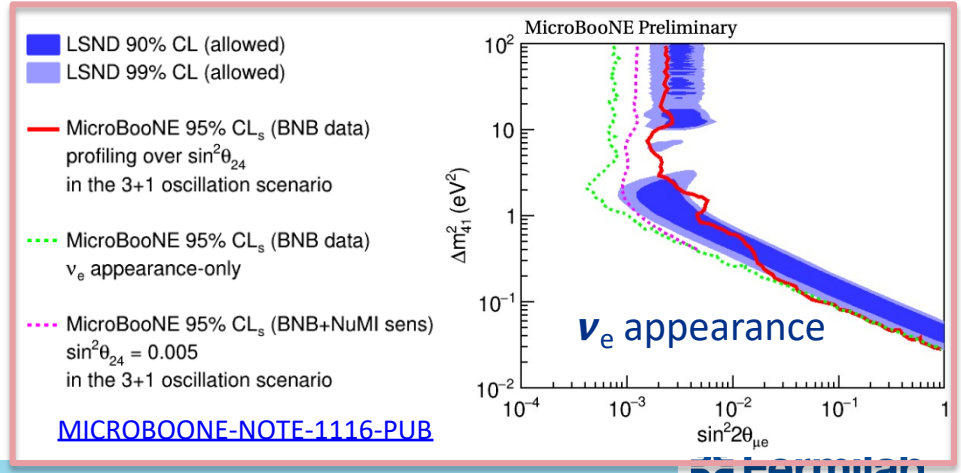
Phys. Rev. Lett. 130, 011801 (2023)

Fermilab

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

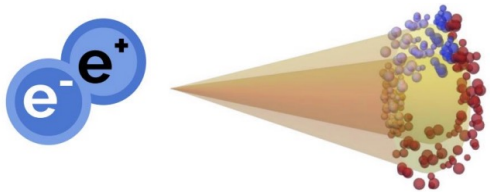
- When $\sin^2\theta_{24}$ approaches the BNB intrinsic ratio of ν_e/ν_μ -> sensitivity degrades.
  - ν_e disappearance can cancel out ν_e appearance.
- Since BNB and NuMI beams have different ratios of ν_e/ν_μ -> degeneracy between the oscillation parameters can be broken.
  - **Improves the sensitivity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



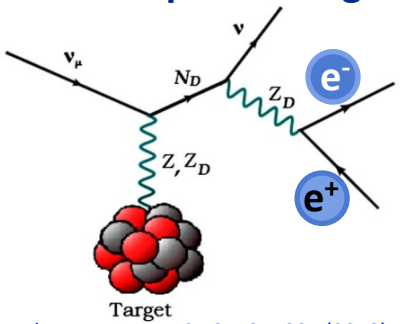


If not γ or e-, what else could it be? BSM explanations?

- 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!

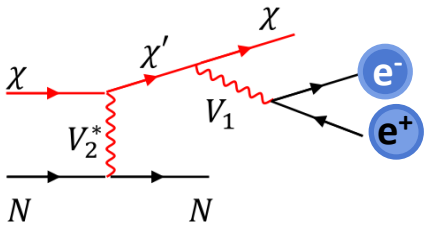


HNL Upscattering



Phys. Rev. Lett. 121 24, 241801 (2018)
Phys. Rev. D 99 071701 (2019)
Phys. Lett. B 820 136531 (2021)

Dark Matter Upscattering

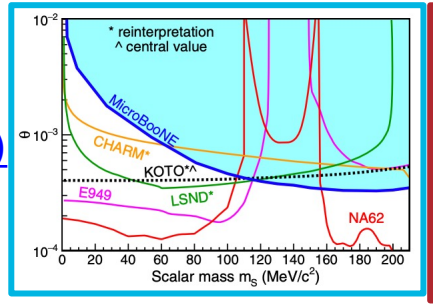


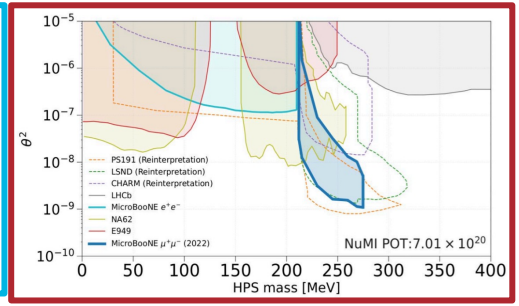
Phys. Rev. Lett. 129 11, 111803 (2022)

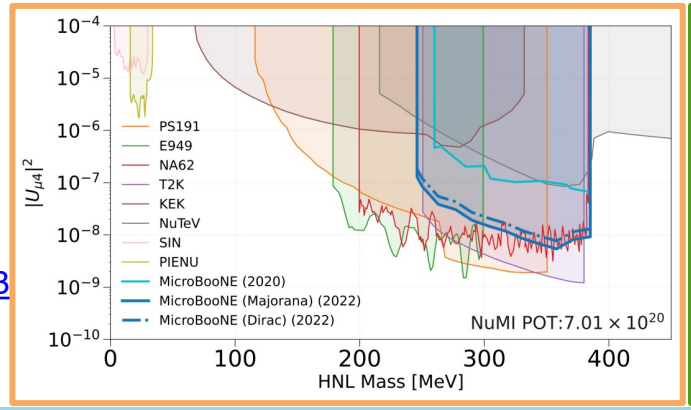
Other BSM Searches in MicroBooNE

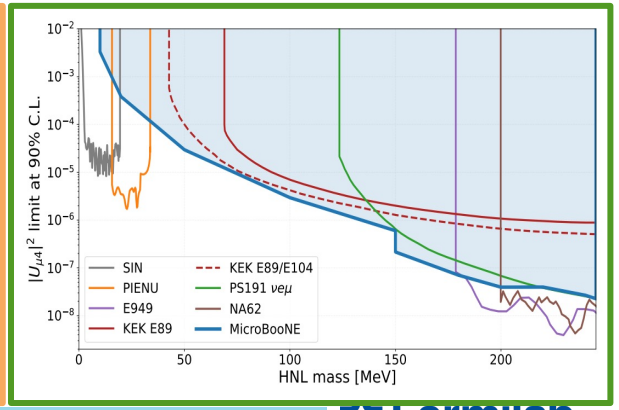
- **Higgs Portal Scalars (HPS):**
  - e+e- -> Phys. Rev. Lett. 127, 151803 (2021)
  - μ+μ- -> Phys. Rev. D 106 9, 092006 (2022)
- **Heavy Neutral Lepton (HNL):**
  - μ+π- or μ-π+ (Majorana) & μ-π+ (Dirac) in BNB -> Phys. Rev. D **101**, 052001 (2020)
  - μ+μ- & μπ in NuMI-> Phys. Rev. D 106 9, 092006 (2022)
  - e+e- & π^0 -> 2310.07660 [hep-ex] (accepted by PRL ~2 weeks ago!)
- **Neutron-antineutron oscillation**
  - 2308.03924 [hep-ex]
- **Dark tridents**
  - MICROBOONE-NOTE-1118-PUB
- **Millicharged particles**

New Results!



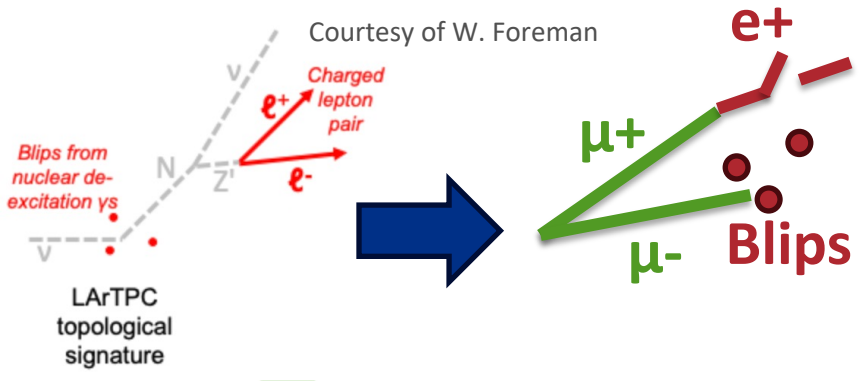


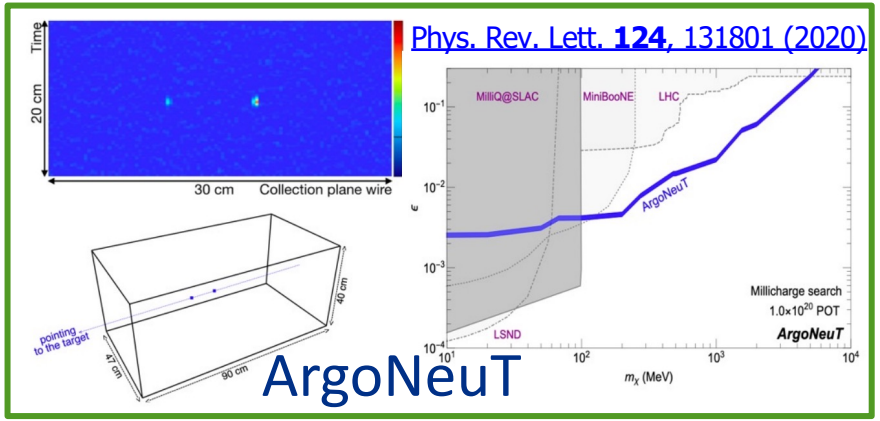




MeV-Scale Physics – What can it be used for?

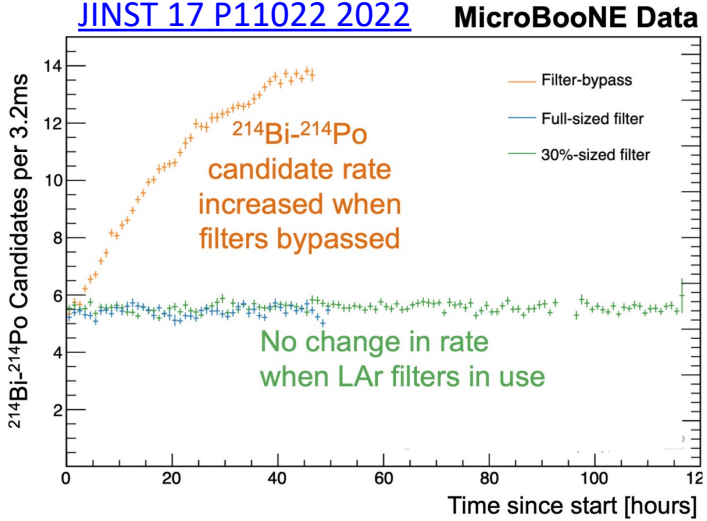
- LArTPCs events include MeV-Scale blips that can come from hadronic interactions.
- Identifying specific particle topological features and improve background rejection could improve sensitivity to some BSM signatures
  - Potential in charge-sign discrimination for μ+/- & π+/-
- Can we do any physics 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.





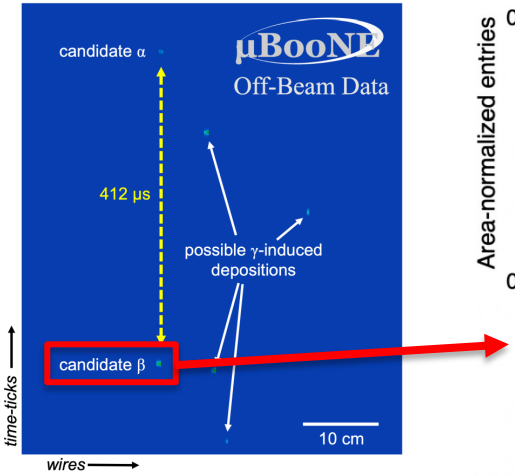
MeV-Scale Physics with MicroBooNE – Radon Search

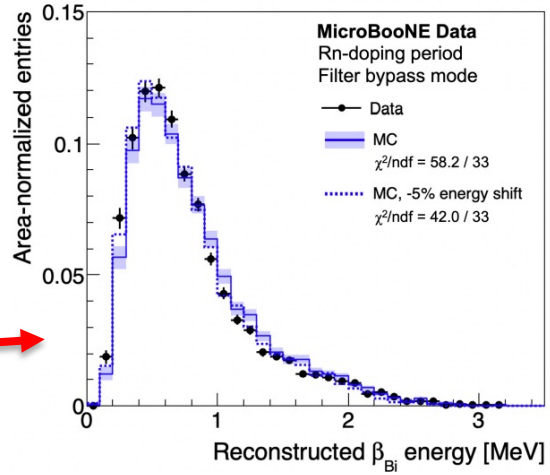
JINST 17 P11022 2022



- 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!

arXiv:2307.03102 (under PRD review)





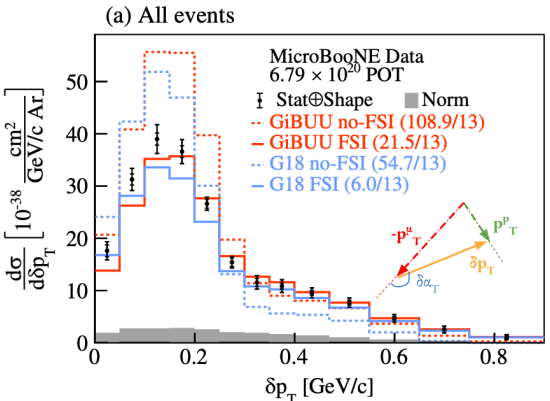
- Measured the ambient radon through Bi(β)-Po (α).
  - Good β-spectrum reconstruction - These are **very low energy events** for LArTPCs! ("MeV-blips").
- Measured an ambient radon rate **of 0.38 mBQ/kg** at a 95% CL upper limit outside of the Rn-doping period.
- DUNE Rn requirement: < 1 mBQ/kg.

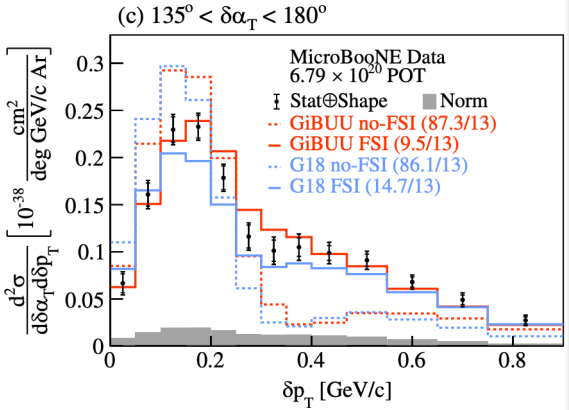
MicroBooNE Extensive Cross Section Program

- 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!

- **CC Inclusive**
  - 1D & 2D νμ CC inclusive @ BNB
    Phys. Rev. Lett. 123, 131801 (2019)
  - 1D νμ CC Eν @ BNB
    Phys. Rev. Lett. 128, 151801 (2022)
  - 3D CC Eν @ BNB
    arXiv:2307.06413, submitted to PRL
  - 1D νe CC inclusive @ NuMI
    Phys. Rev. D105, L051102 (2022)
    Phys. Rev. D104, 052002 (2021)
- **Pion production**
  - 3D CC Eν @ BNB
    arXiv:2307.06413, submitted to PRL
  - νμ NCπ0 @ BNB
    Phys. Rev. D 107, 012004 (2023)

- **Rare channels**
  - Λ production @ NuMI
    Phys. Rev. Lett. 130, 231802 (2023)
  - η production @ BNB
    arXiv:2305.16249, submitted to PRL
- **CC0π**
  - 1D νe CCNp0π @ BNB
    Phys. Rev. D 106, L051102 (2022)
  - 1D & 2D νμ CC1p0π Kinematic Imbalance @ BNB
    Phys. Rev. Lett. 131, 101802 (2023)
    Phys. Rev. D 108, 053002 (2023)
    arxiv:2310.06082, submitted to PRD
  - 1D νμ CC1p0π @ BNB
    Phys. Rev. Lett. 125, 201803 (2020)
  - 1D νμ CC2p @ BNB
    arXiv:2211.03734
  - 1D νμ CCNp0π @ BNB
    Phys. Rev. D102, 112013 (2020)



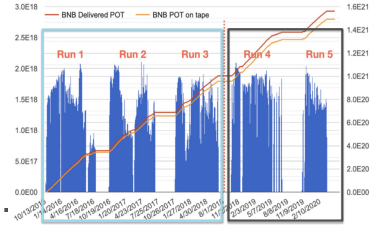


Phys. Rev. Lett. 131, 101802 (2023) Phys. Rev. D 108, 053002 (2023)

- **CC inclusive**
  - νμ CC inclusive @ NuMI
  - νe /νμ ratios @ BNB, NuMI
  - 3D Eν , Eμ , hadronic energy @ NuMI & BNB
  - νe @ NuMI
- **Pion production**
  - νμ CC1π+ @ BNB, NuMI
  - νμ CCNπ @ NuMI
  - 1D νμ CCπ0 @ BNB
  - 2D νμ CC/NC π0 @ BNB
  - 2D νe,μ NCπ0 @ BNB
  - Kinematic imbalance
- **CC0π**
  - νμ CC0π inclusive @ BNB
  - 2D νμ CCNp0π @ BNB
  - 1D νe CC0πNp @ NuMI
  - 1D νμ NC1p0π @ BNB
- **Rare & novel channels**
  - νμ CC kaon @ BNB, NuMI
  - MeV-scale physics
  - Neutrons @ BNB

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 NCΔ → Nγ at 94.8% CL.**
    - Coherent + inclusive photon searches are underway as alternative to NCΔ.
    - 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/

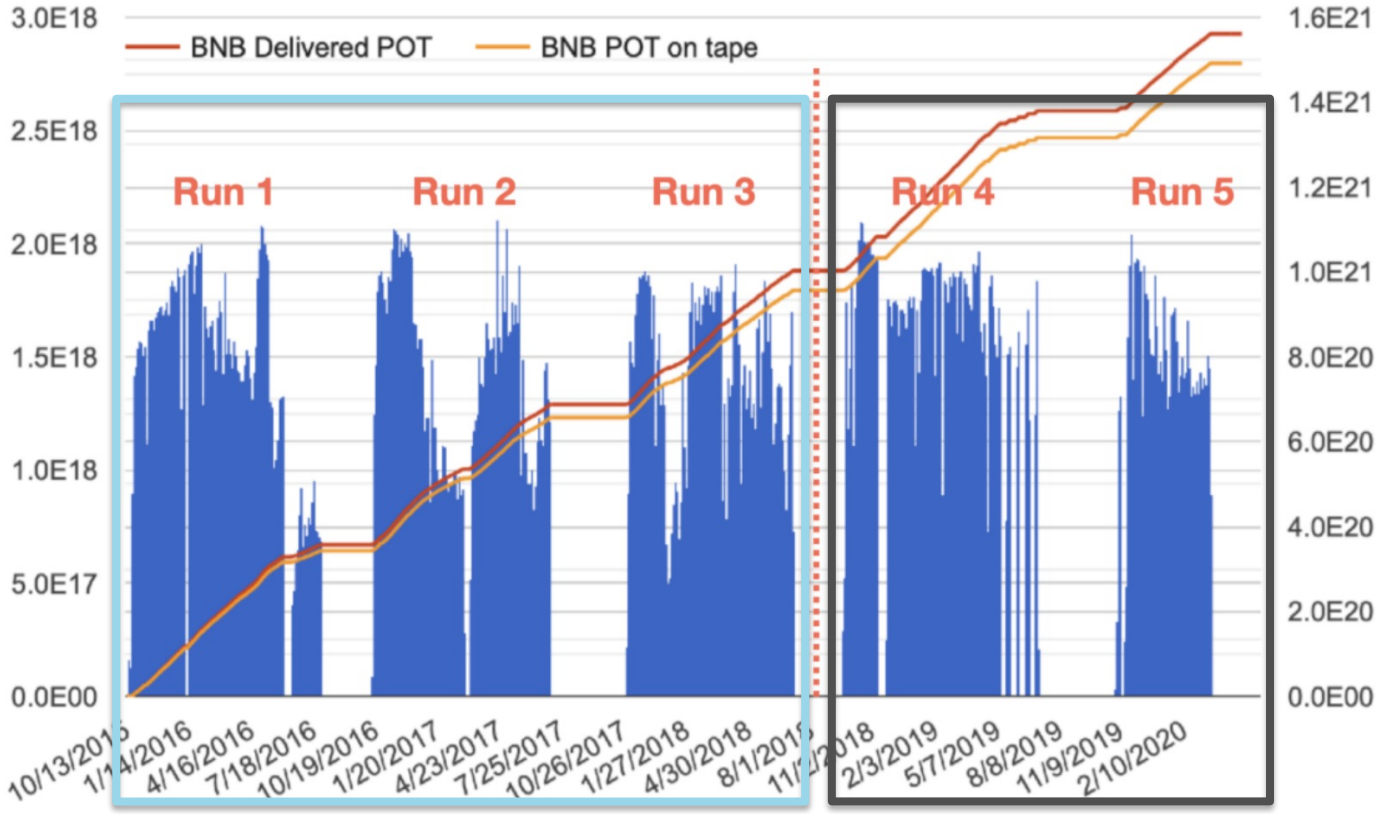
~62 papers… so far!

Many more in preparation!

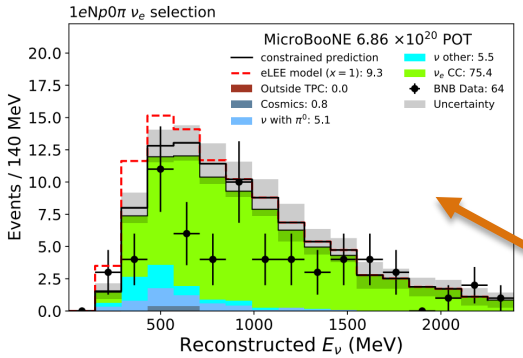
Running over 5 years of Beam Data!

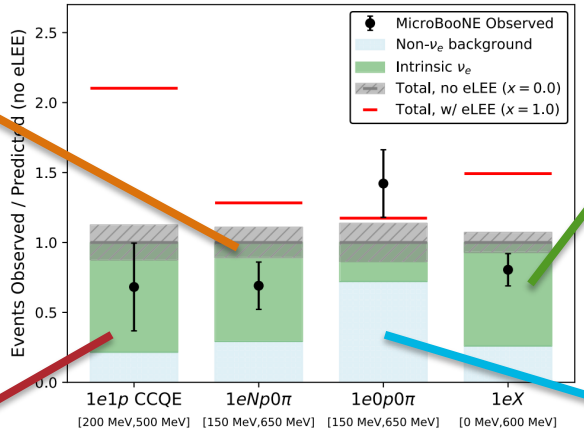
- All analyses published so far only use ~1/2 of the full dataset.

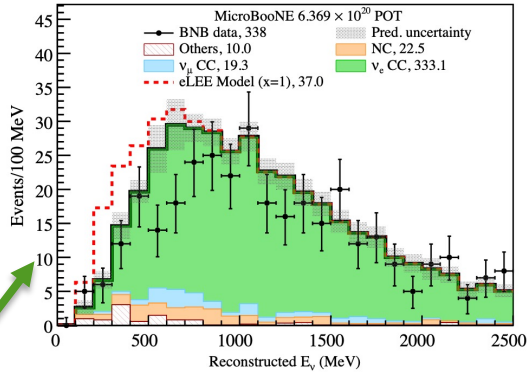
- Expect to have full dataset analyses start to come out in 2024!

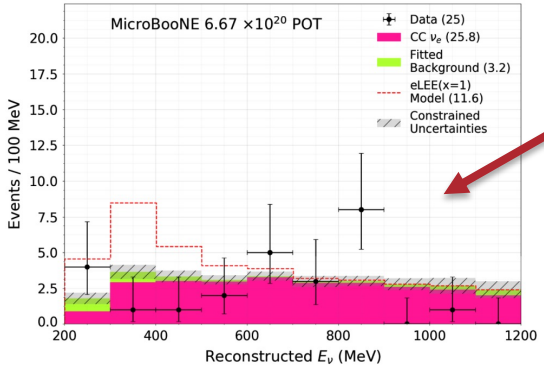


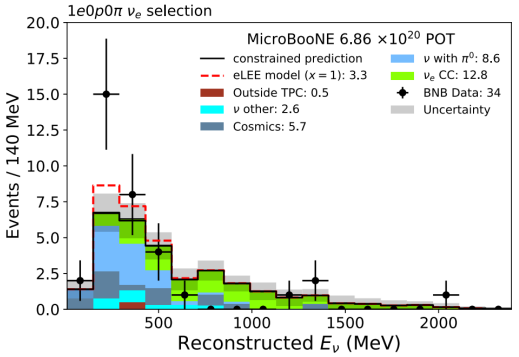
Low Energy Excess Searches Through Electrons









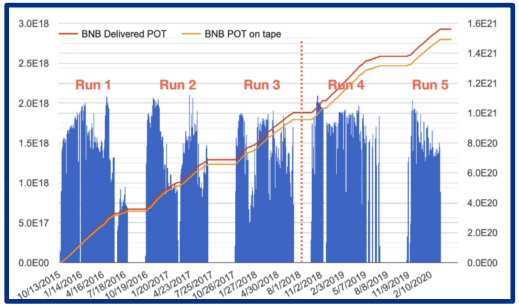


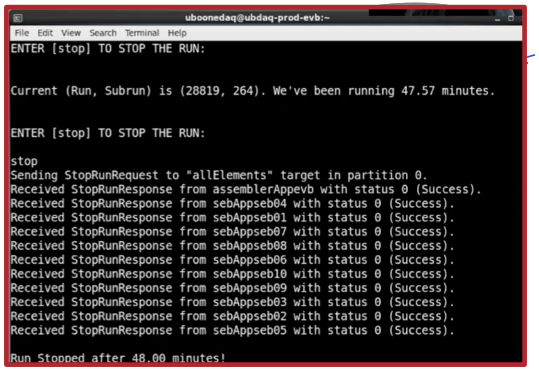
MicroBooNE Timeline

Low energy excess anomalies

Construction + Installation

Operations





Mid 2015

2020

Late 2021

2007

Late 2015

2021

2023

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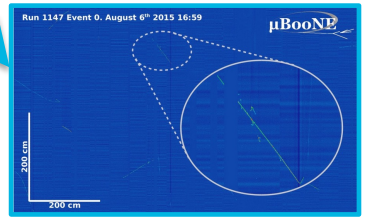
R&D Period

Decommissioning

Argon Venting



Filling + Commissioning

A Proposal for a New Experiment

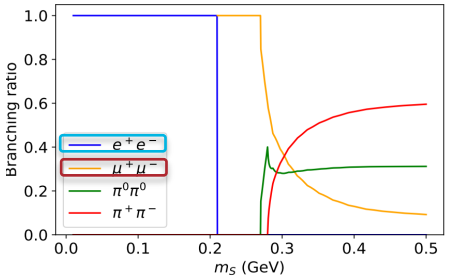
Using the Booster and NuMI Neutrino Beamlines: MicroBooNE

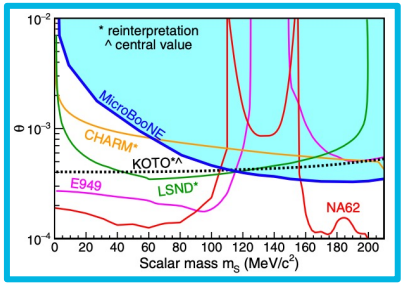
[Link to proposal]

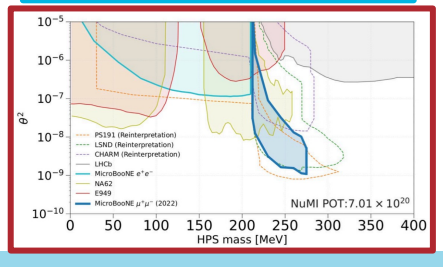
Fermilab

Other BSM Searches in MicroBooNE

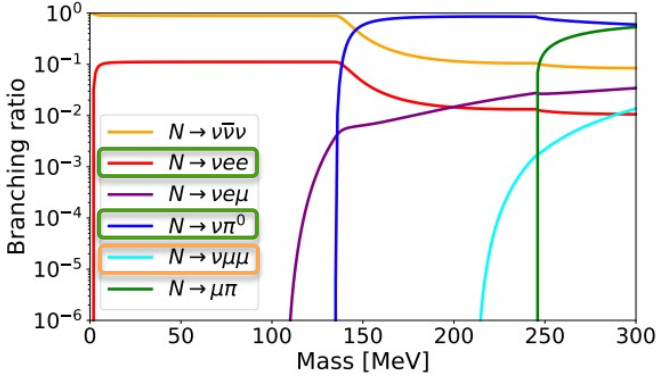
Higgs Portal Scalars (HPS)

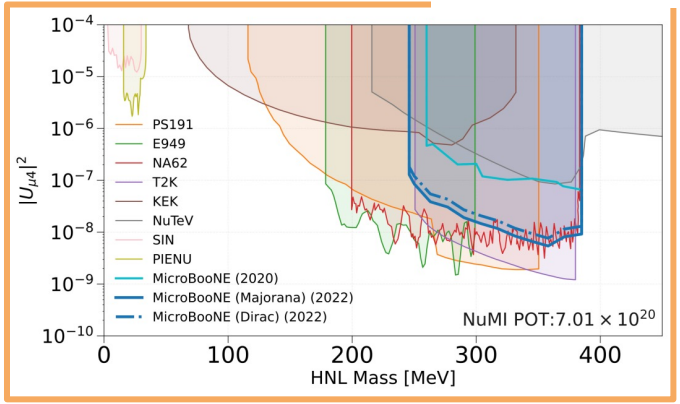


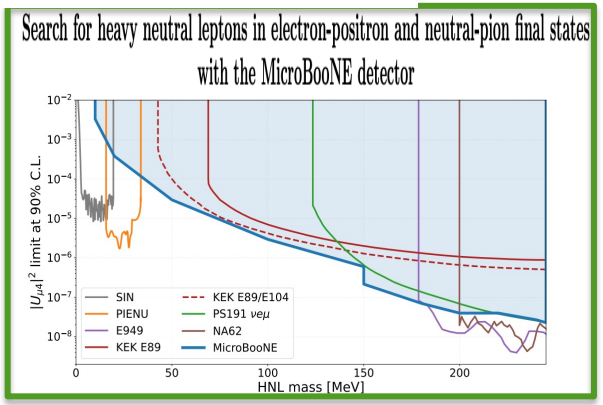




Heavy Neutral Lepton (HNL)







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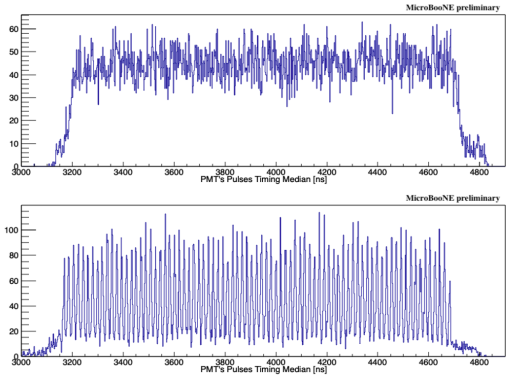
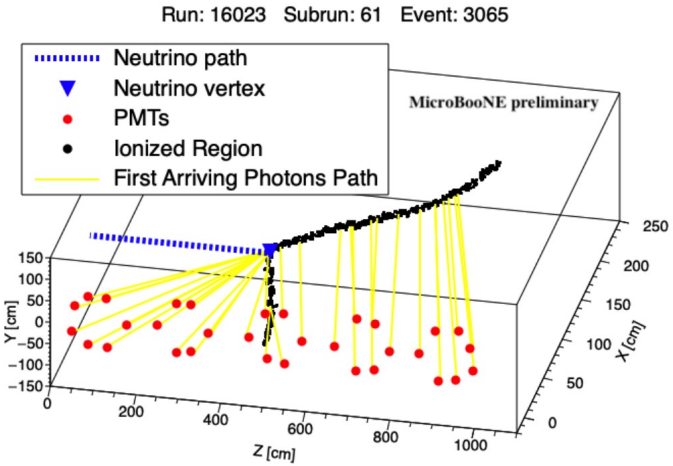
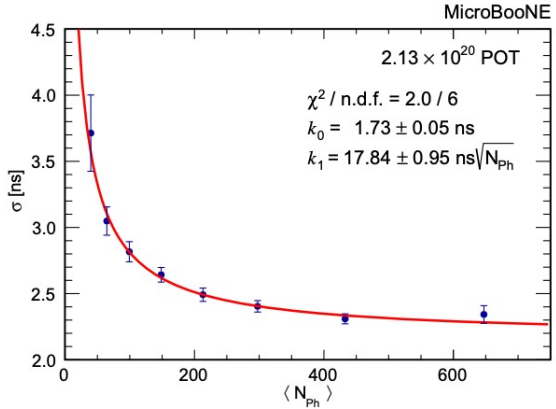


Figure 7: Top: neutrino interaction timing distribution before the reconstruction. Bottom: neutrino interaction timing distribution after the reconstruction. The 81 bunches composing the ~1.6 μs beam pulse sub-structure are well visible after the reconstruction.



[Phys. Rev. D **108**, 052010 (2022)]

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



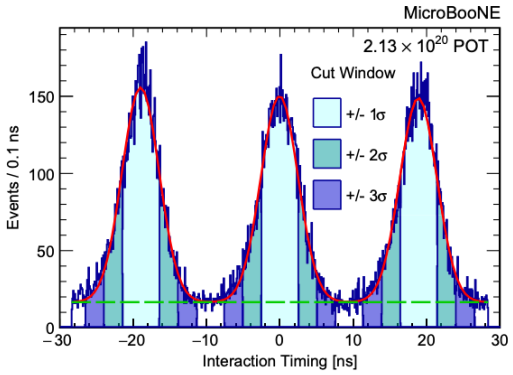


FIG. 12. Interaction timing resolution as a function of the total number of photons detected.

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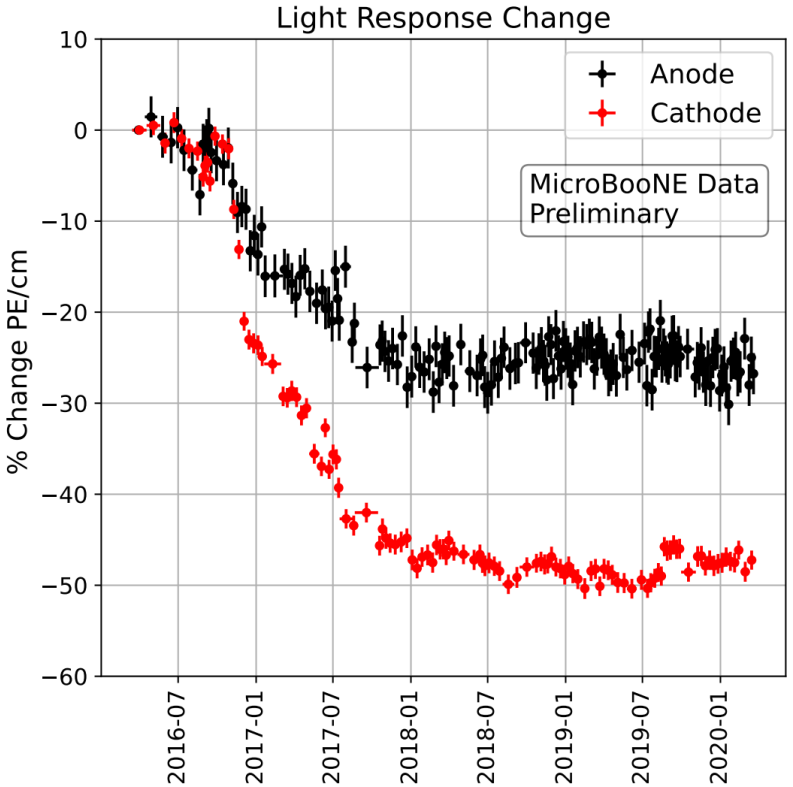
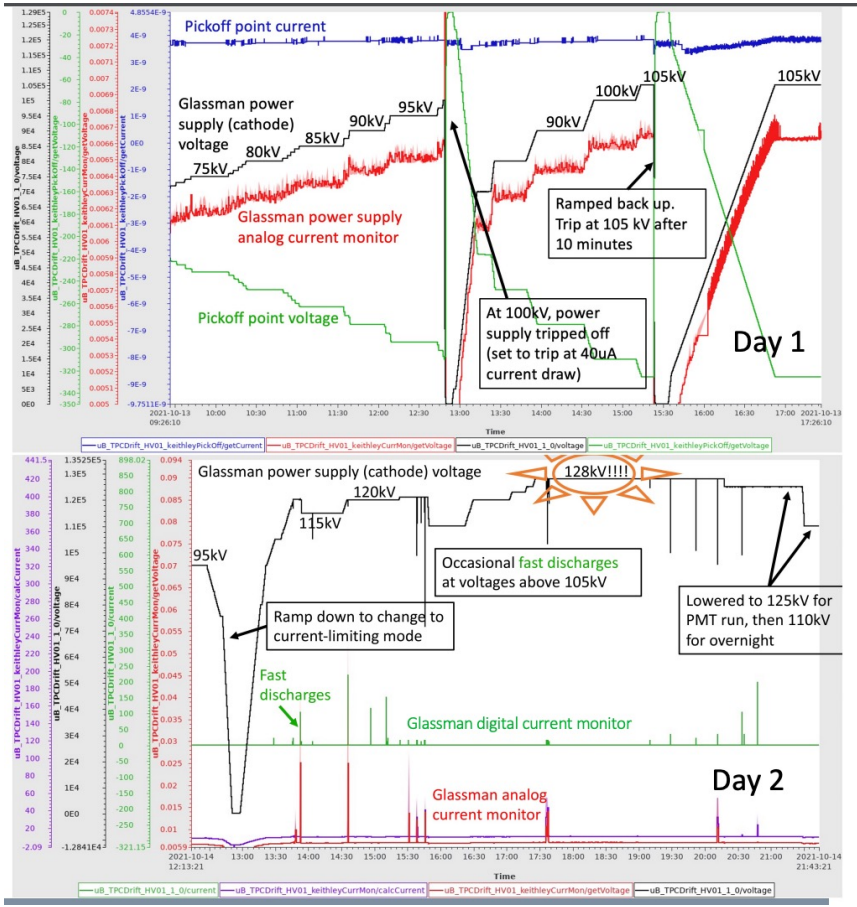
Time-Based Light Yield Stability Measurement – Results

- 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 ½ 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.



Fermilab

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.