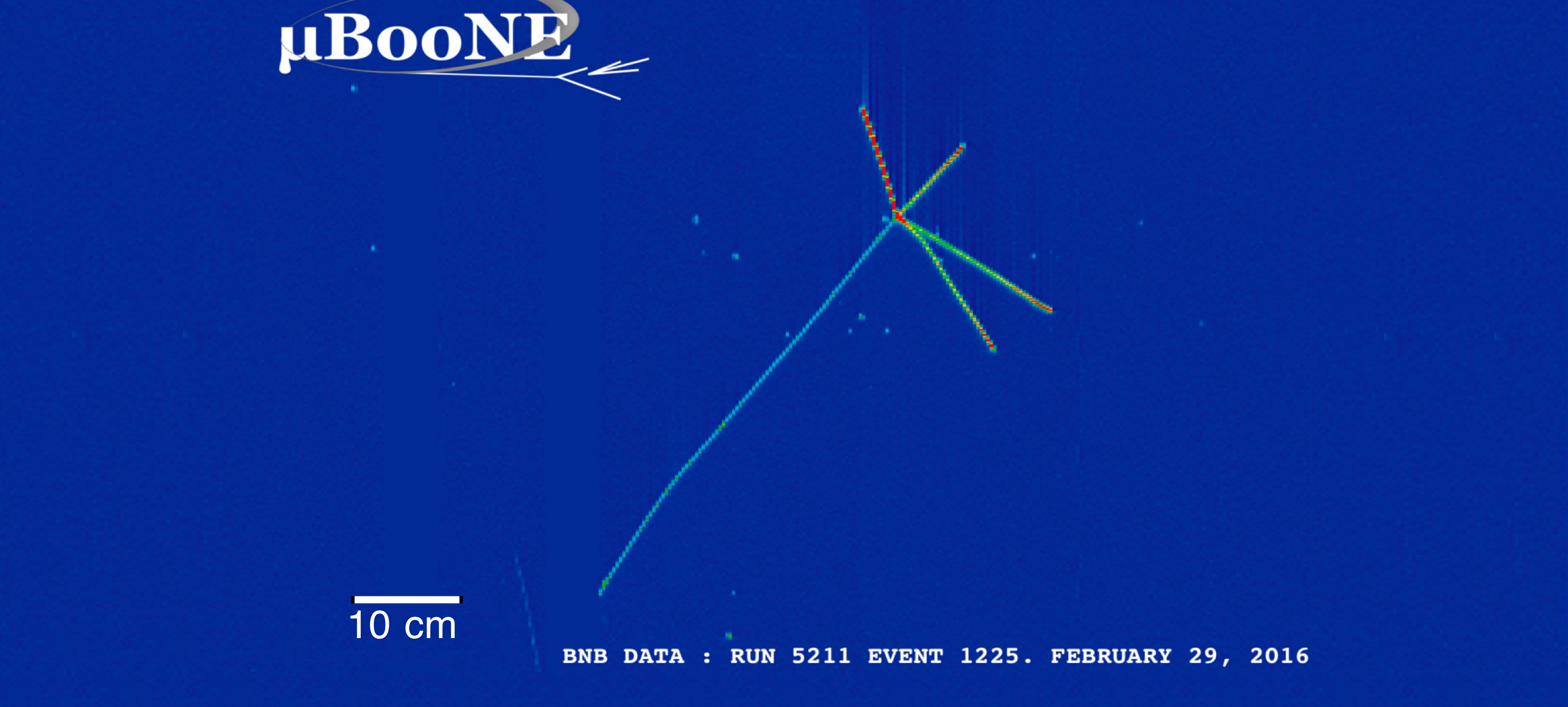

Latest Results from the MicroBooNE Experiment

Tanaz Angelina Mohayai, Indiana University
For the MicroBooNE Collaboration

TAU2023, Dec. 7, 2023

Big Picture

- Exploiting the long- to short-baseline oscillation experiments to unravel the remaining puzzles in ν physics
  - Do neutrinos oscillate differently than anti-neutrinos? Which neutrino is the lightest?
  - Do we understand everything about neutrino interactions?
  - Are there more than 3 types of neutrinos?
  - What Beyond Standard Model physics can we search for in ν experiments?

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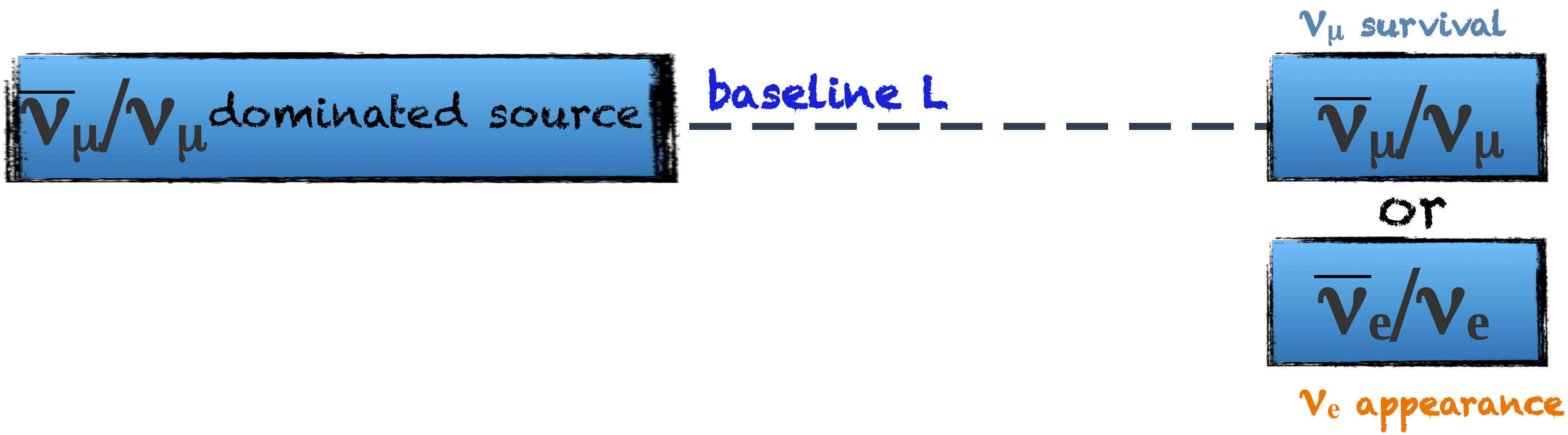
Neutrino Oscillations



- **Neutrino oscillations considered one of the strongest pieces of evidence of BSM physics**
  - Modeled with various parameters, **mixing angle, θ_{ij}**, **mass splitting squared term, Δm^2_{ij}**, **CP violating term, δ_{CP}**, **baseline, L**, and **neutrino energy, E_ν**

simplified 2 flavor probability, e.g. ν_e appearance probability, $P(\nu_\mu \rightarrow \nu_e)$

$$\sin^2(2\theta)\ \sin^2(1.27\Delta m^2_{21} L/E)$$

Neutrino Oscillation Parameters

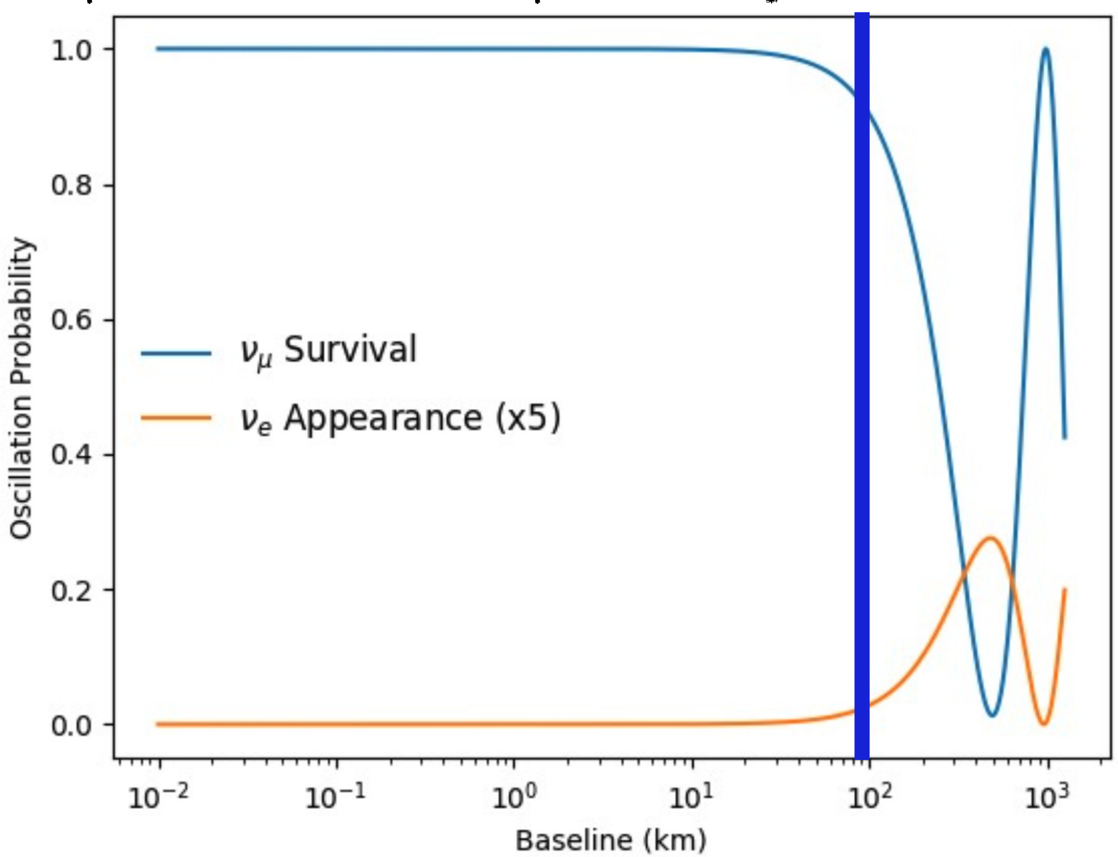
NuFIT 5.2 (2022)

	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$

Oscillation Probability

- **Based on current oscillation parameters:**
  - ★ No oscillations expected for 1 GeV neutrinos, at **baselines < 100 km**, i.e. the **survival probability ≈ 1** & **appearance probability ≈ 0**
  - ★ Oscillations at baseline < 100 km could suggest larger splitting due to an additional 4th neutrino

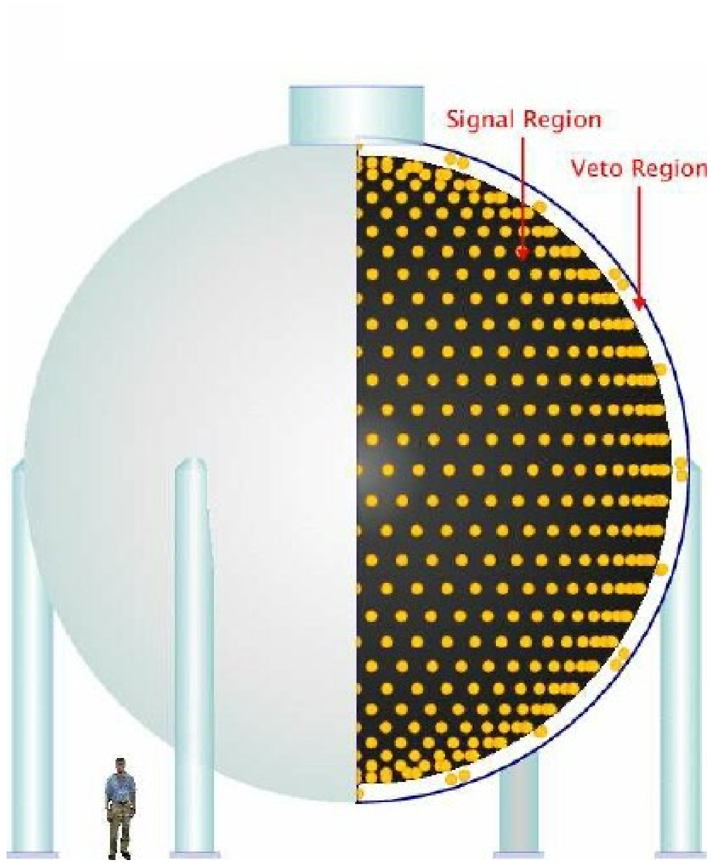
example of oscillation probability of ~1 GeV neutrinos



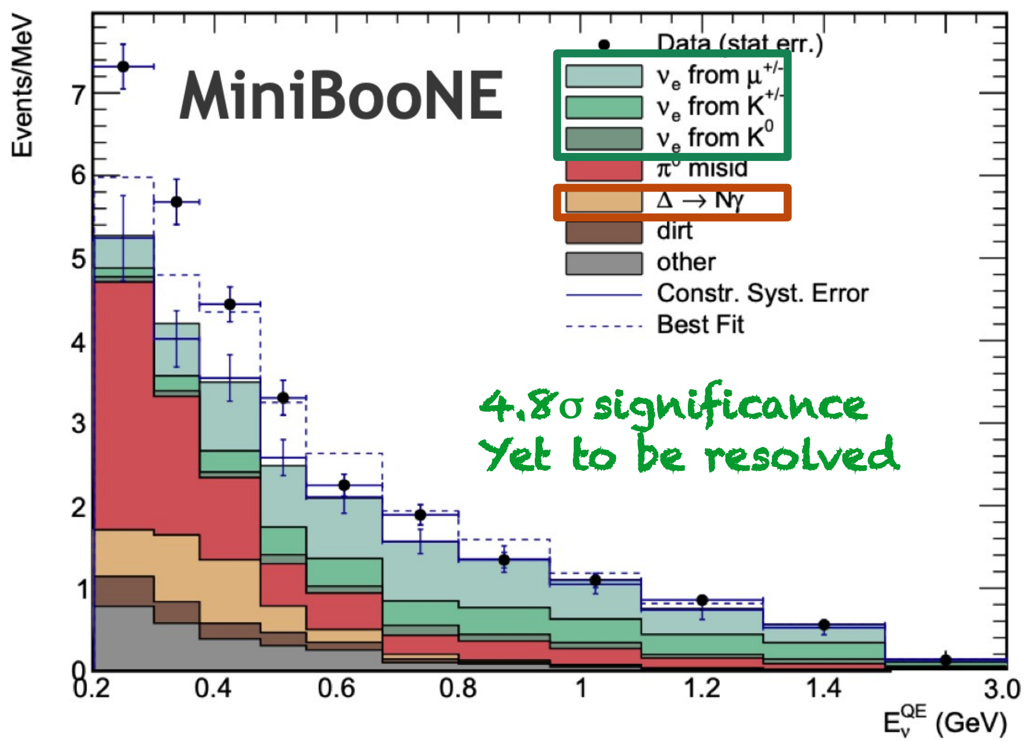
credit: E. Worcester

MiniBooNE at Short-baseline

- A Cherenkov detector that operated for 17 years
- Observed a large excess of events at low energies:
  - If due to **electrons,** then could constitute a possible evidence for ν_e appearance at short-baselines
  - Could also be due to **background photons**



Phys. Rev. D 103, 052002 (2021)



baseline: ~500 m, avg neutrino energy: ~800 MeV

MiniBooNE at Short-baseline

- A Cherenkov detector that operated for 17 years
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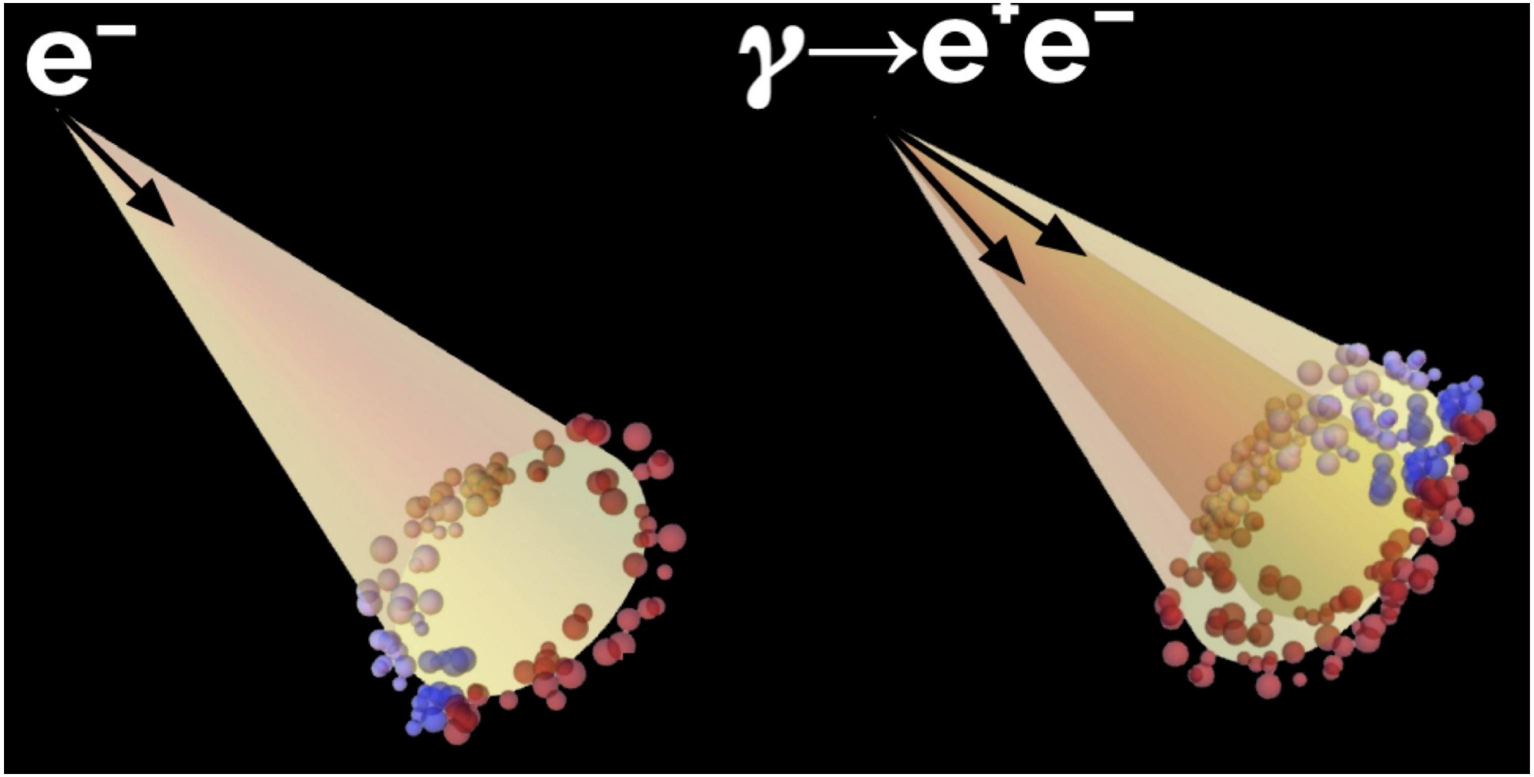
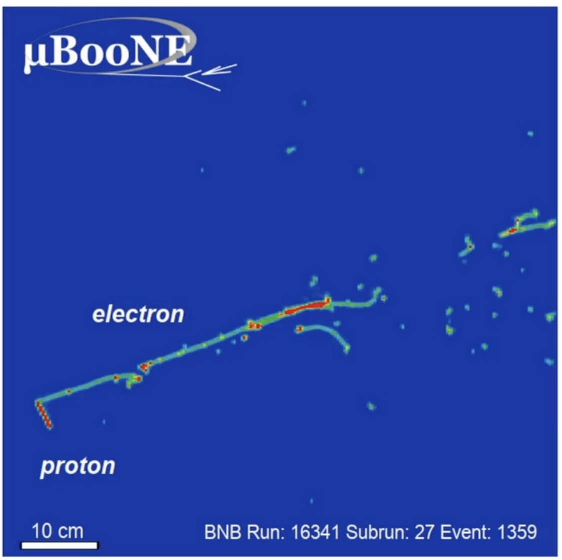
  - If due to **electrons,** then could constitute a possible evidence for ν_e appearance at short-baselines
  - Could also be due to **background photons**

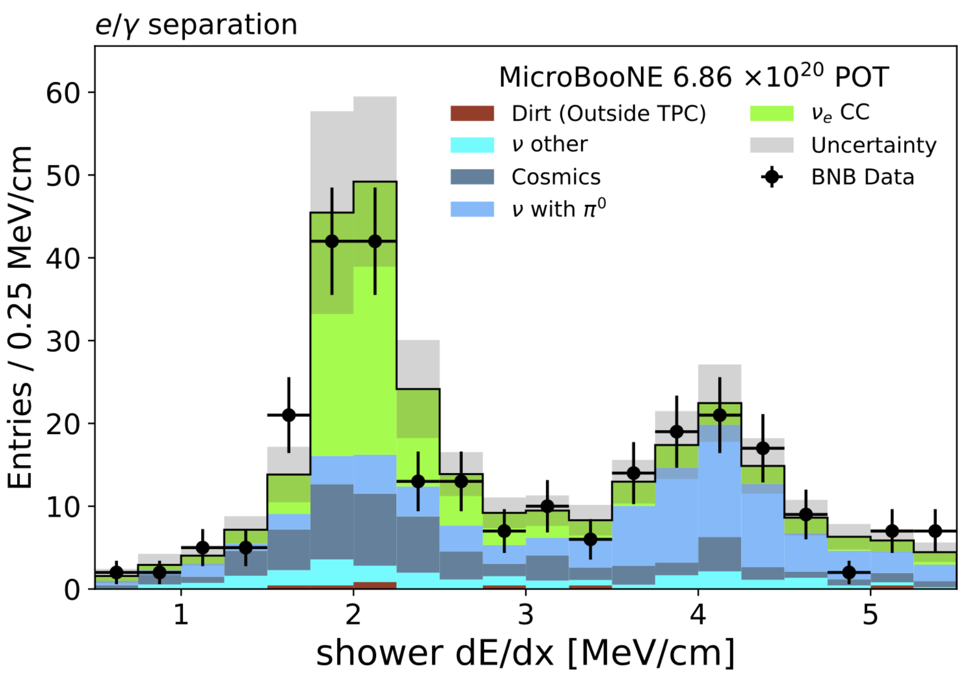
specifically, distinguishing between photons and **electrons** is a challenge in a Cherenkov detector like MiniBooNE

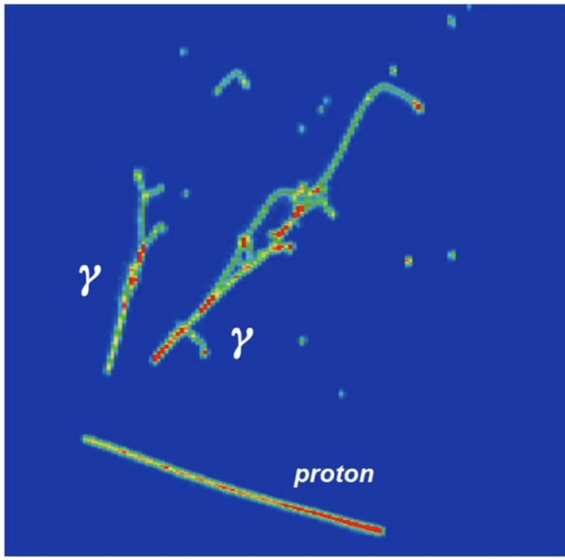


Need for a New Detector Technology

- MicroBooNE employs a **liquid-argon time projection chamber, LArTPC** which can **more efficiently make the distinction between electrons and photons**, using topological and dE/dx information

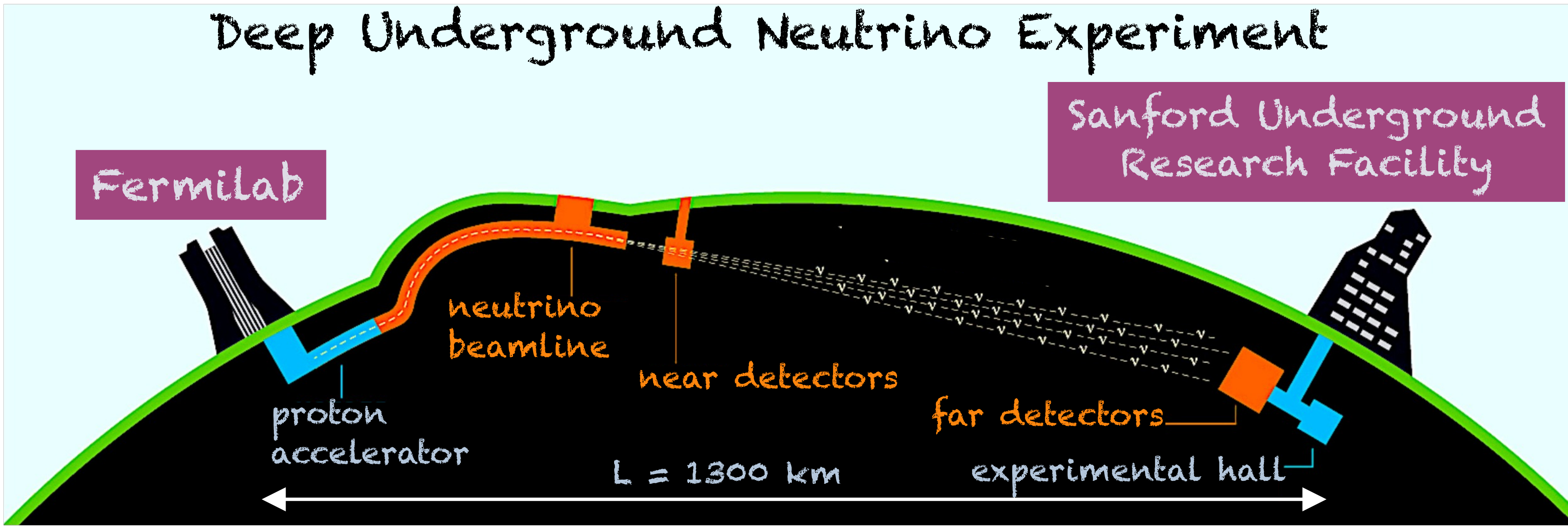






arXiv:2110.14065v3

LArTPCs in a Future Precision Experiment

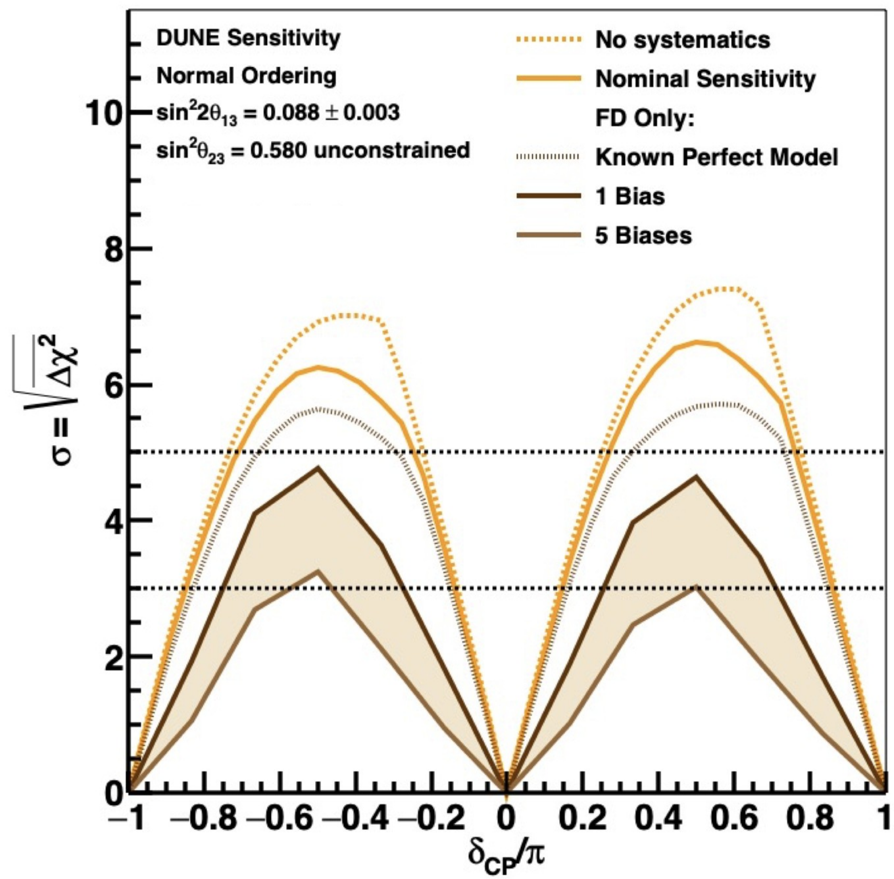


for the first time, a long-baseline (1300 km) oscillation experiment will use argon as its nuclear target for precision studies of ν oscillations

Challenges of Future Precision Experiments

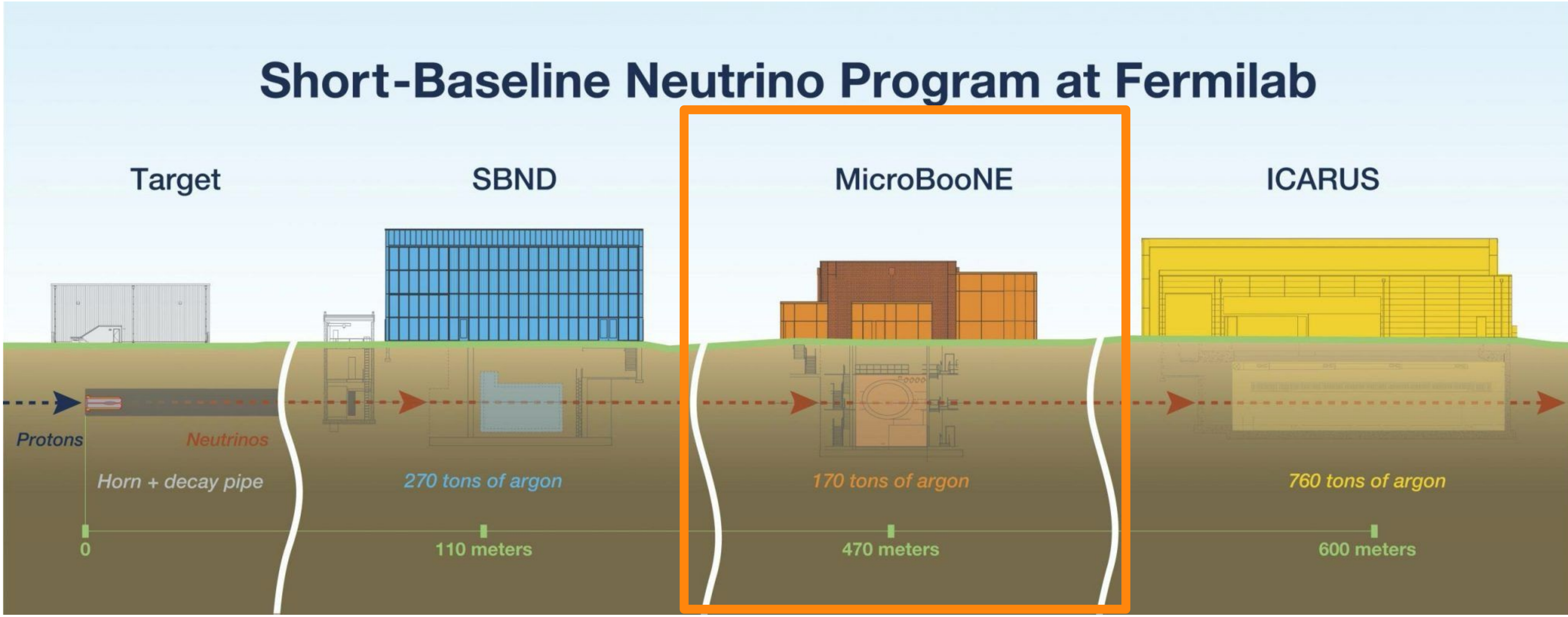
- Future precision experiments, e.g. DUNE, require few percent uncertainties
  - Includes uncertainties on neutrino interactions, detector systematics, & flux
  - Ultimate sensitivity in DUNE achieved only via a robust constraint on these, particularly **dominant uncertainties from neutrino interactions**
  - Leverage **existing LArTPC experiments** to address the current scarcity of data on argon

arXiv:2103.13910



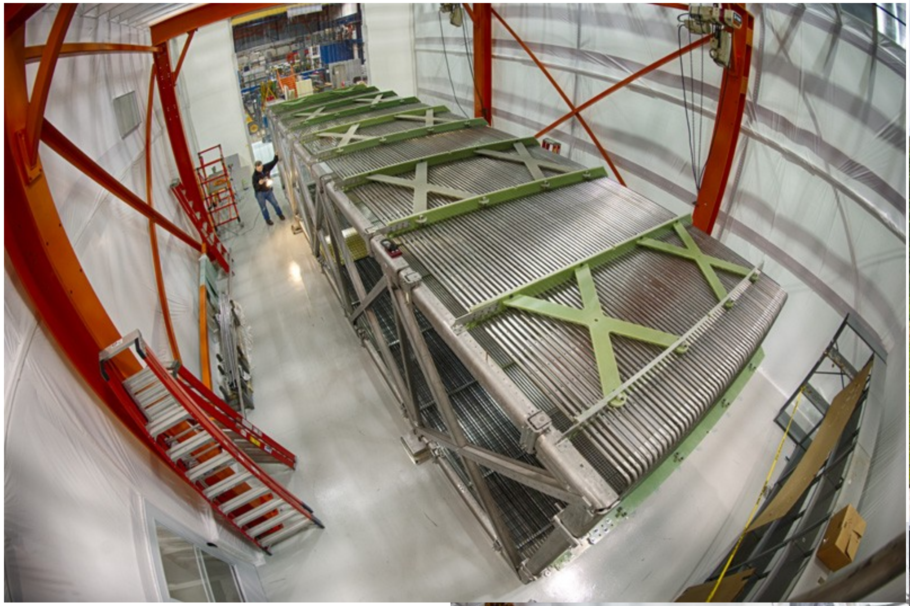
Fermilab Short-baseline Program

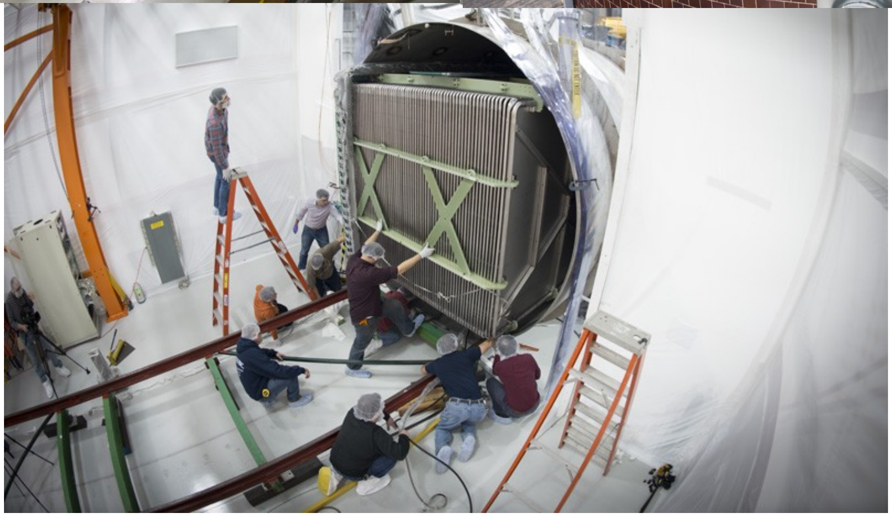
- MicroBooNE is the pioneer LArTPC in this program, operated from 2015 to 2021 in the same ν beam as MiniBooNE
- Combined with SBND and ICARUS, its goals are to investigate short-baseline oscillations both in appearance and survival modes, **neutrino-argon interaction cross-sections, advancements in LArTPC detector physics, and BSM signature searches**



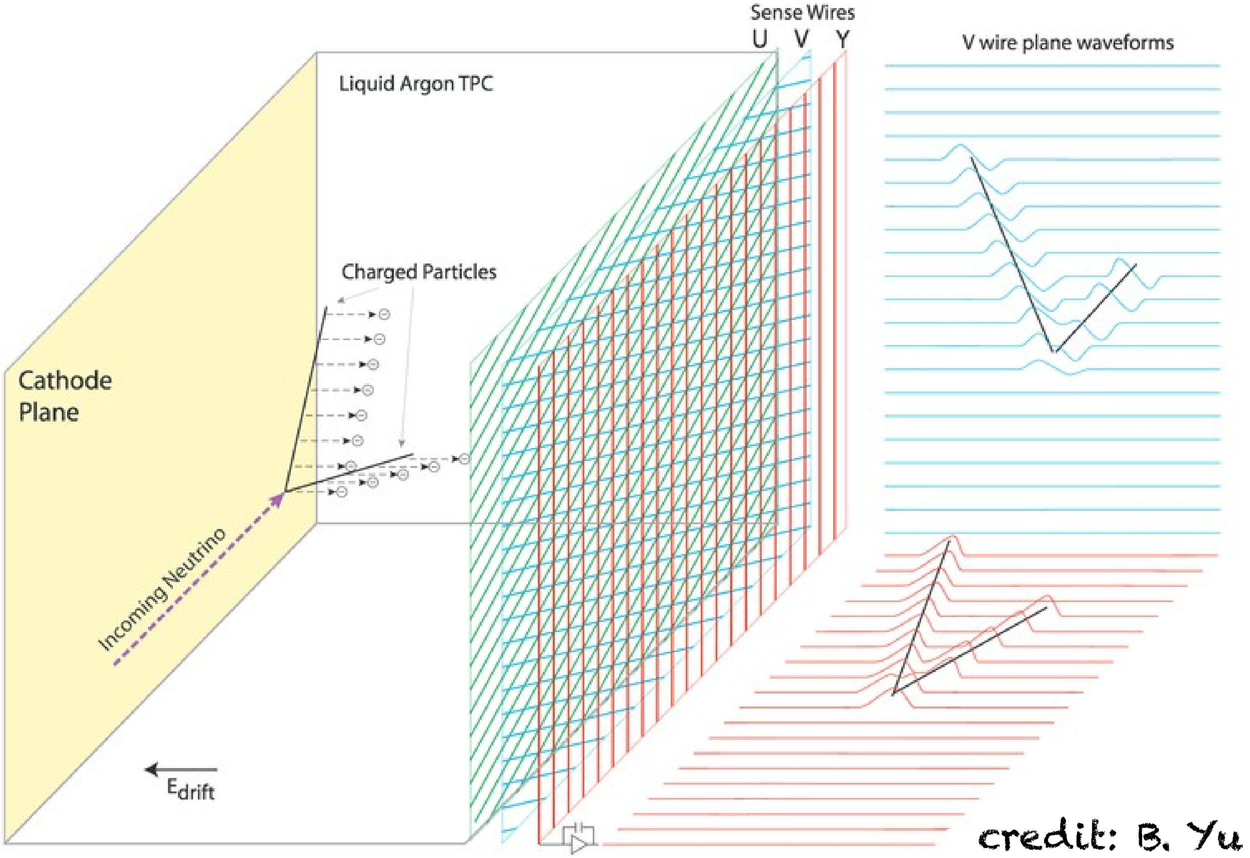
MicroBooNE Detector

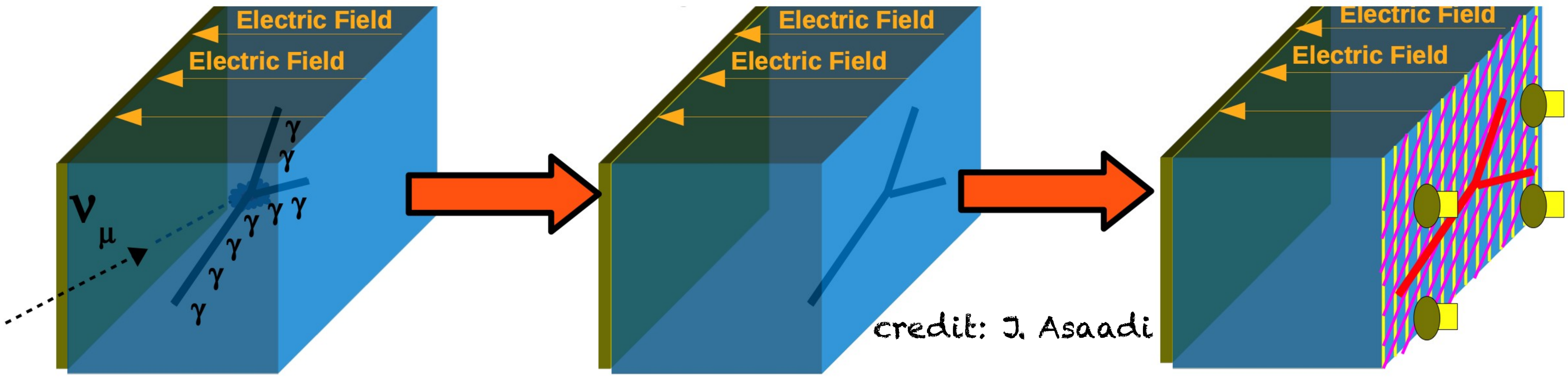
- 170 tonne LArTPC
- World's largest dataset of neutrino interactions on argon



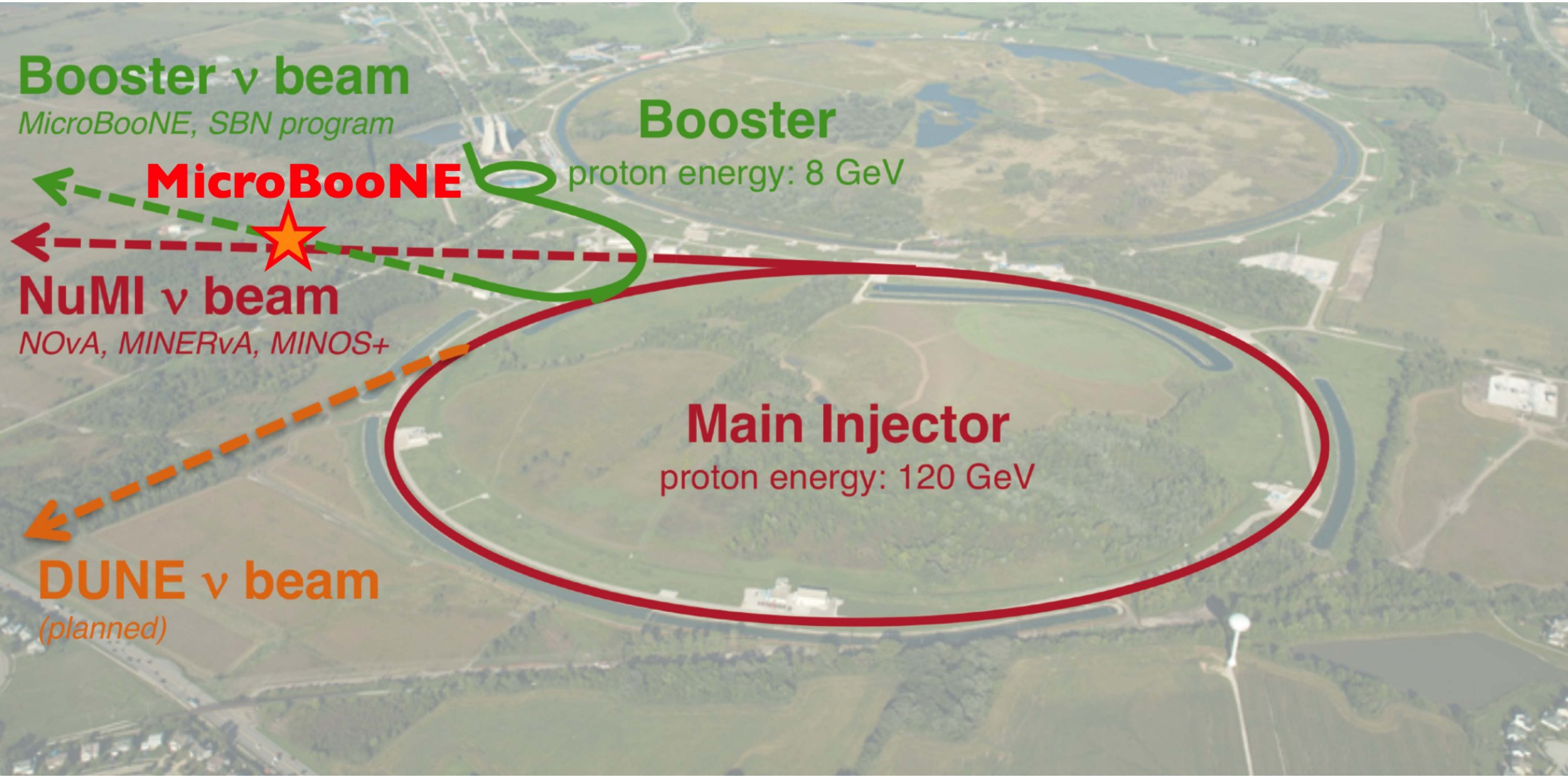


Working Principle of the Detector



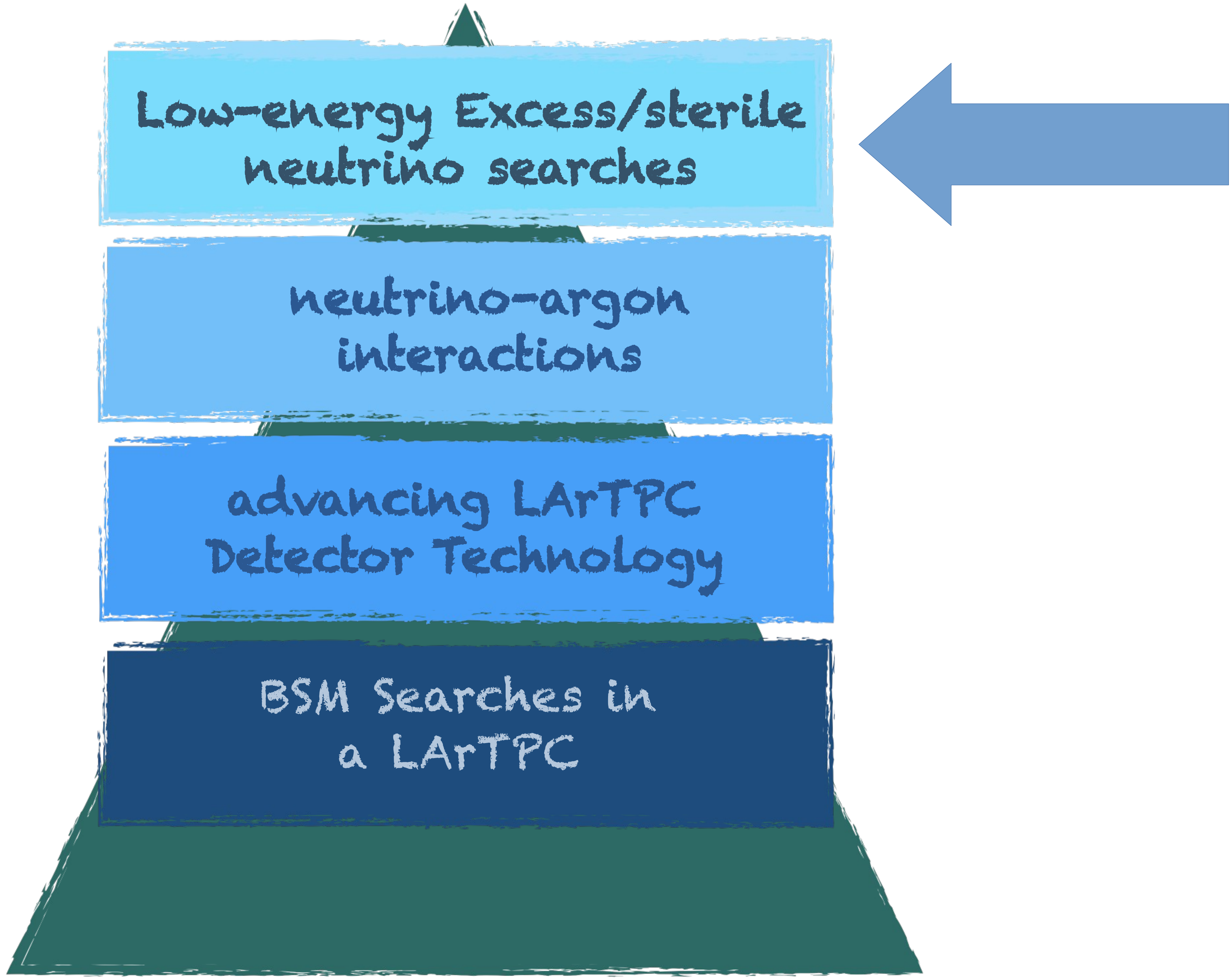


The Beam



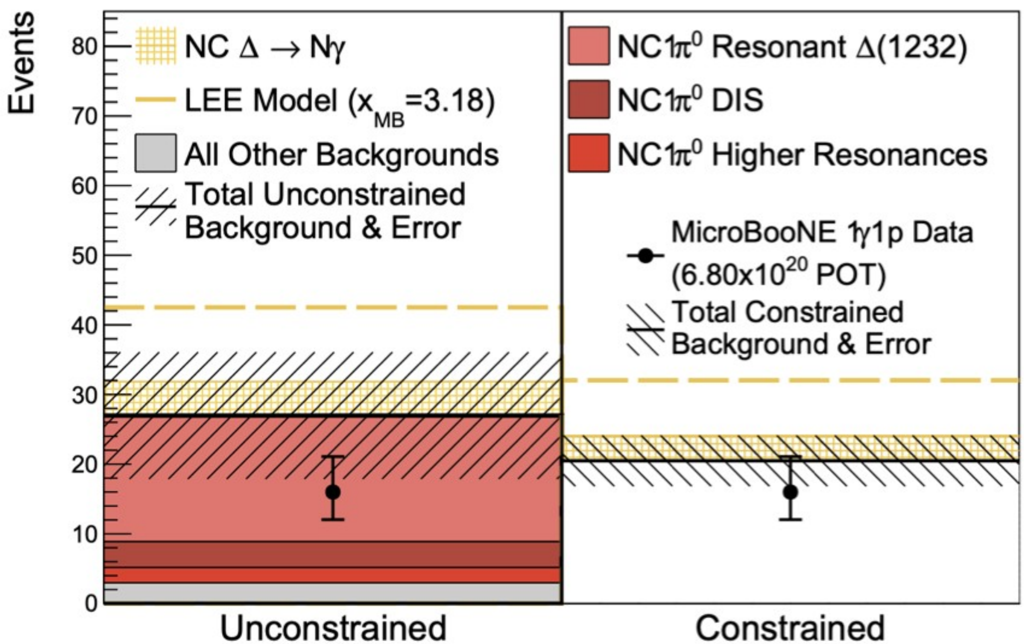
Booster ν beam
MicroBooNE, SBN program
MicroBooNE
NuMI ν beam
NOvA, MINERvA, MINOS+
DUNE ν beam
(planned)
Booster
proton energy: 8 GeV
Main Injector
proton energy: 120 GeV

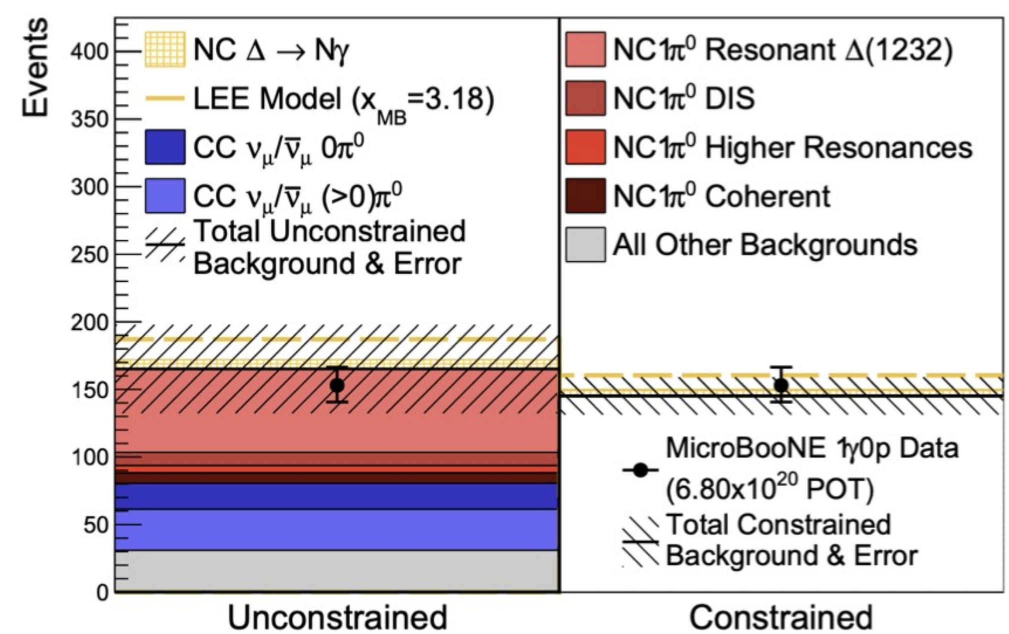
MicroBooNE Physics Program



LEE Search in MicroBooNE – NC Δ→Nγ

- Two channels were investigated:
  - 1γ1p and 1γ0p
- Achieved the most stringent constraint on neutrino-induced NC Δ→Nγ on any nuclear target
- Rules out photons from NC Δ→Nγ as the cause of the LEE, 94.8% C.L.





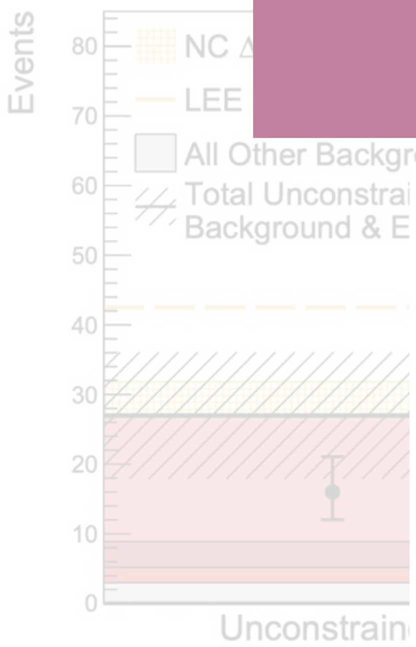
1γ1p Phys. Rev. Lett. 128, 111801 (2022) 1γ0p

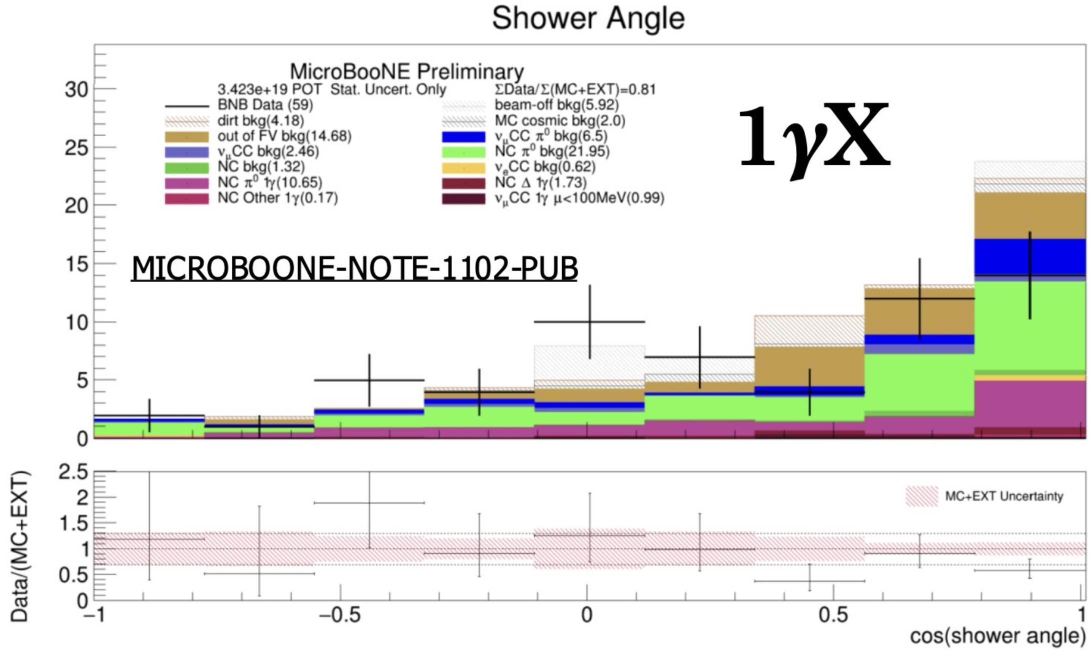
LEE Search in MicroBooNE – NC Δ→Nγ

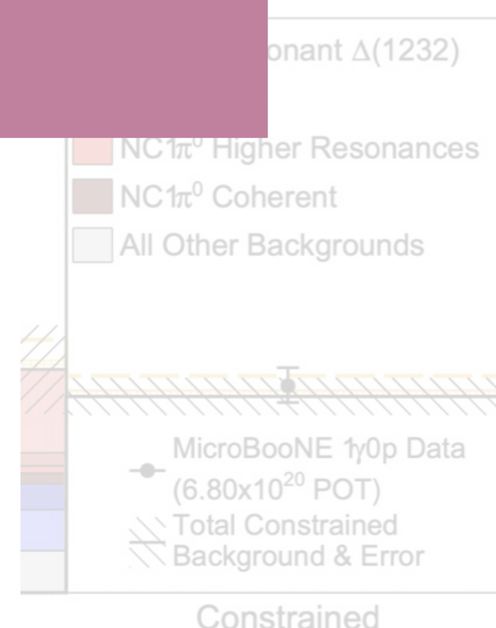
- Two ch
  - 1γ1p a
- Achieve … Δ→Nγ on any r
- Rules o … 8% C.L.

Looking ahead:
more photon searches are underway including inclusive single-photon and Coherent photon searches

MICROBOONE-NOTE-1104-PUB
MICROBOONE-NOTE-1102-PUB
MICROBOONE-NOTE-1103-PUB



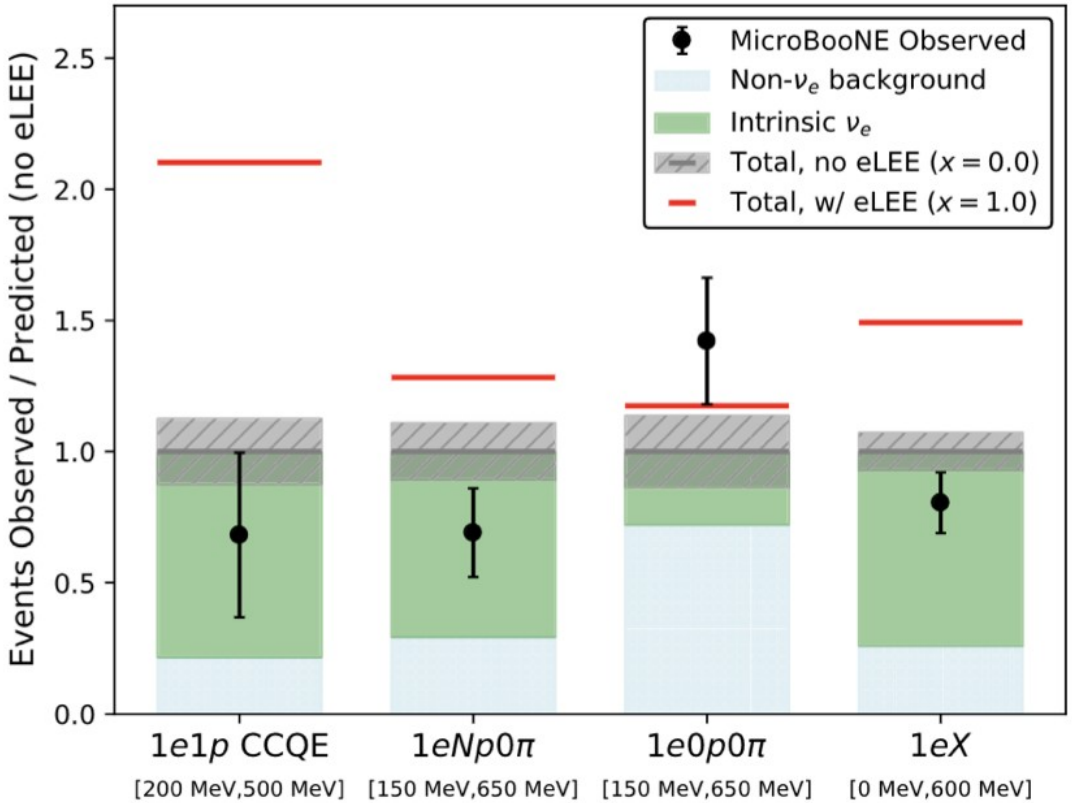




1γ0p

LEE Search in MicroBooNE – Electrons

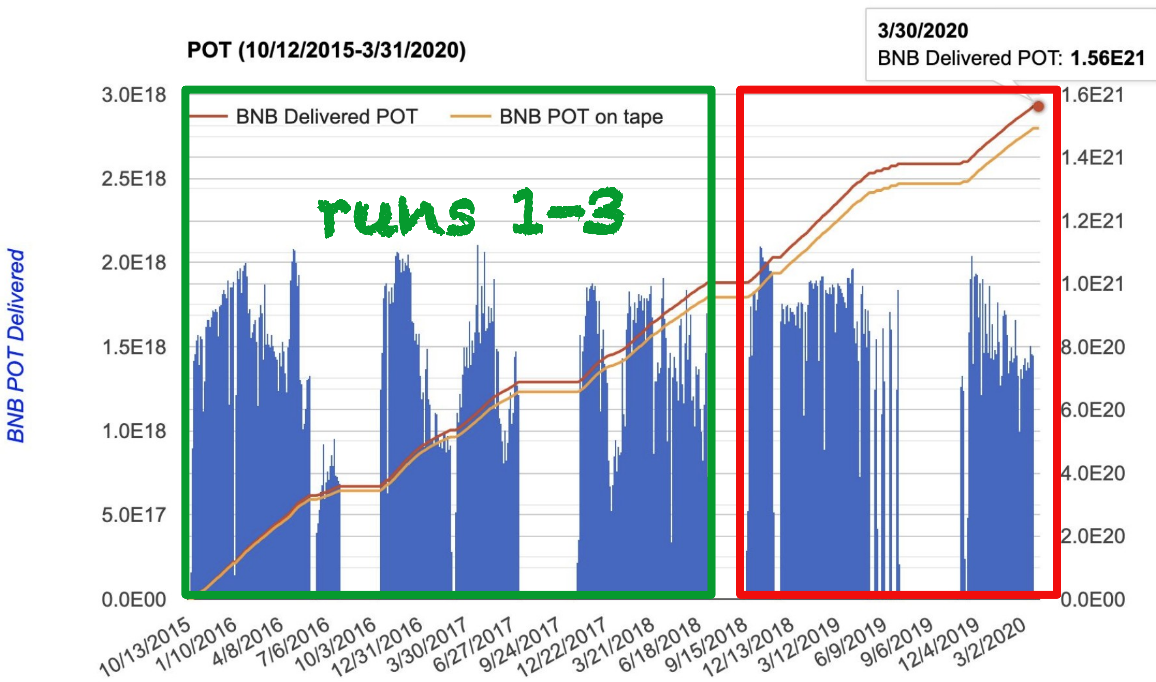
- Is there an excess in ν_e that can point to oscillations at short baselines?
- Various channels with electrons in the final state investigated – Phys. Rev. D 105, 112003 (2022), Phys. Rev. D 105, 112004 (2022), Phys. Rev. D 105, 112005 (2022)
- Rejects electrons as the sole explanation of the LEE at > 97% CL

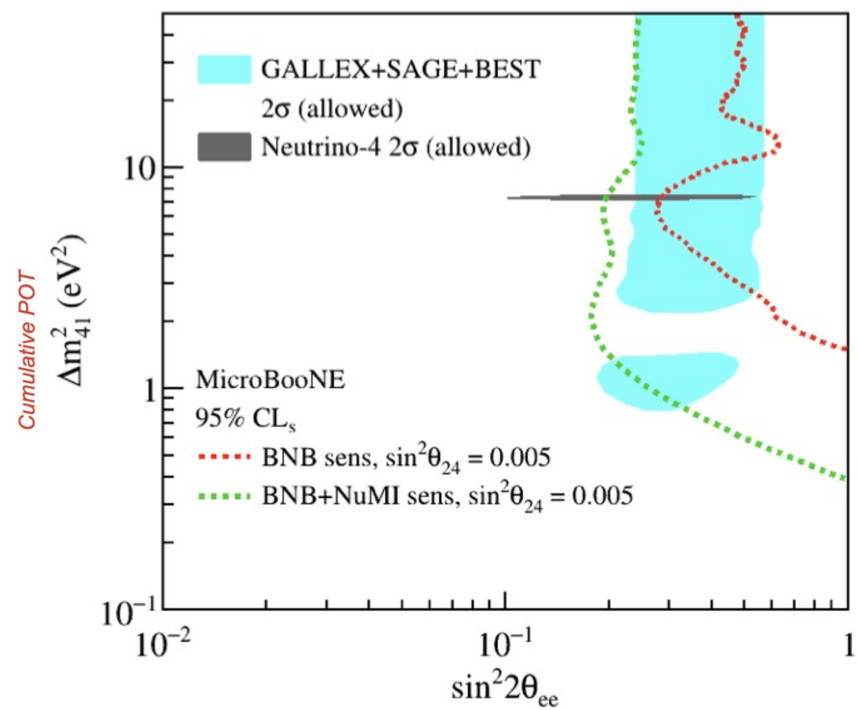


Phys. Rev. Lett. 128, 241801 (2022)

Future Prospects of the LEE Searches

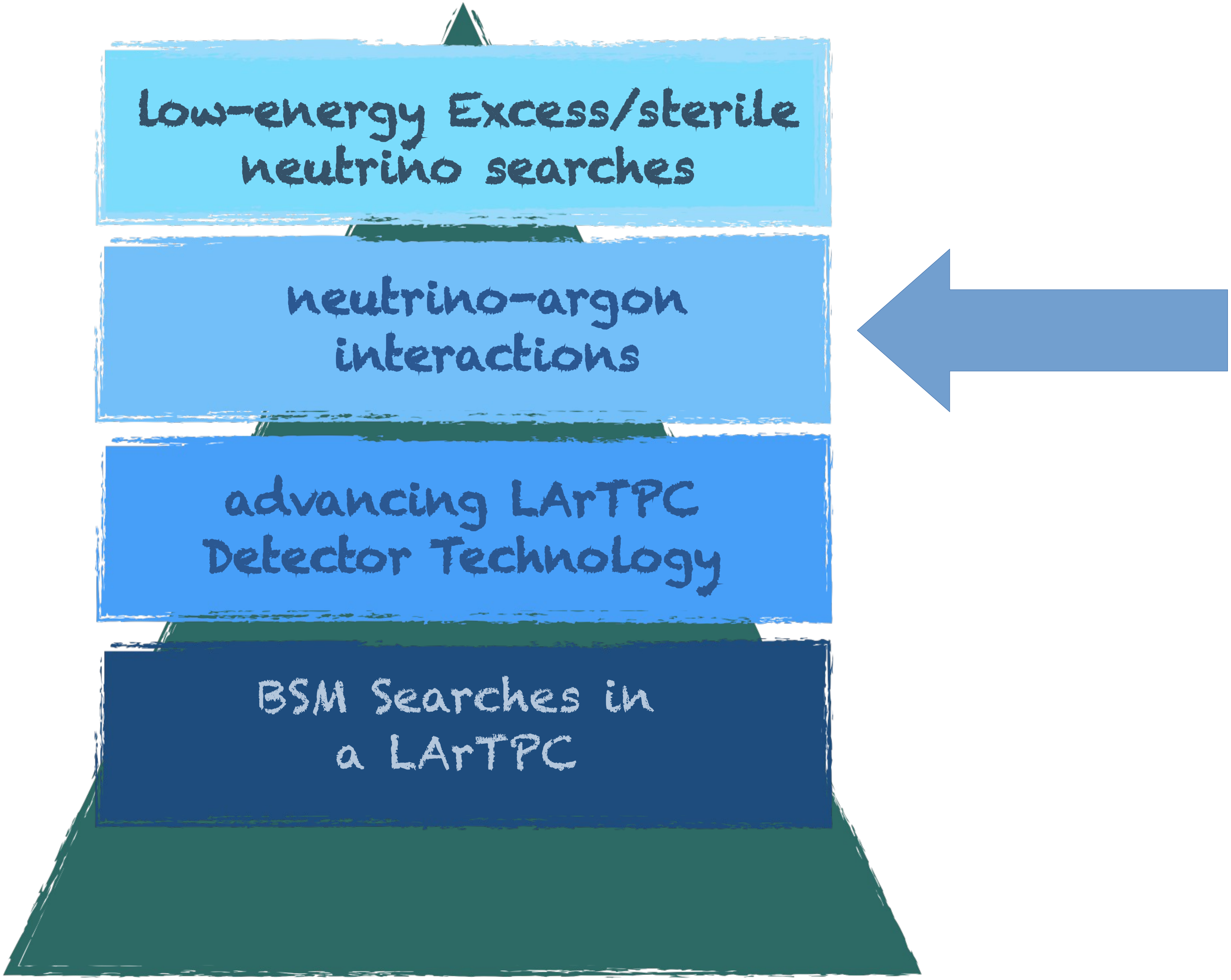
- Only runs 1-3 have been explored for LEE searches so far, more results underway with the remaining data!
- A combined analysis using NuMI and BNB is underway, better sensitivity to other experimental results (mainly due to degeneracy mitigation) expected





MICROBOONE-NOTE-1116-PUB

MicroBooNE Physics Program



MicroBooNE Cross-section Program – Overview

μBooNE

CC inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 3D CC E_ν @ BNB
  arXiv:2307.06413 , submitted to PRL
- 1D ν_e CC inclusive @ NuMI
  Phys. Rev. D105, L051102 (2022)
  Phys. Rev. D104, 052002 (2021)

Pion production

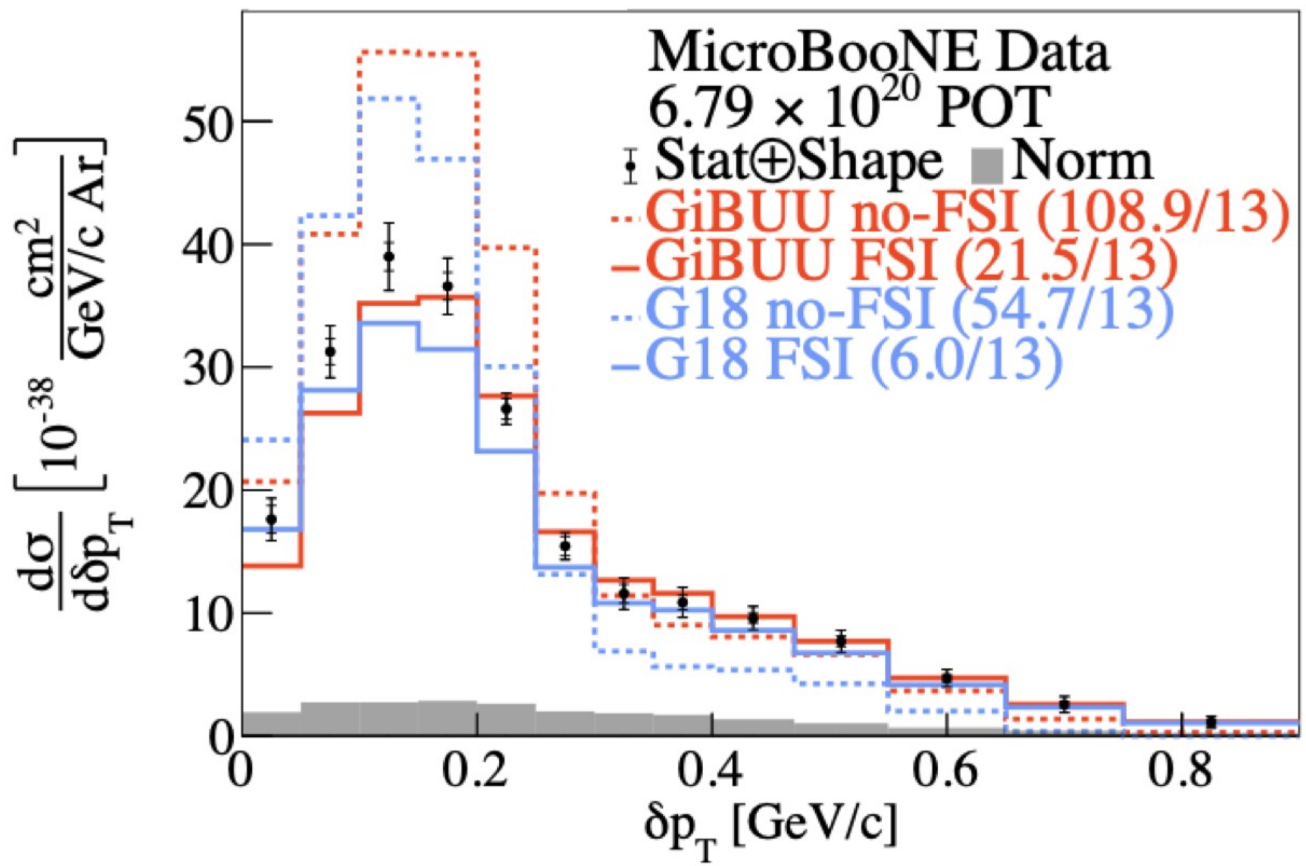
- ν_μ NCπ^0 @ BNB
  Phys. Rev. D 107, 012004 (2023)

CC0π

- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Transverse Imbalance @ BNB
  Phys. Rev. Lett. 131, 101802 (2023)
  Phys. Rev. D 108, 053002 (2023)
- 1D & 2D ν_μ CC1p0π Generalized Imbalance @ BNB
  arXiv:2310.06082, submitted to PRD
- 1D ν_μ CC1p0π @ BNB
  Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CC2p @ BNB
  arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB
  Phys. Rev. D102, 112013 (2020)

MicroBooNE CCQE-like Topology: 1μ1p0π

- First transverse kinematic imbalance measurement on argon target
- Data favors including FSI (Final State Interaction) models in generators

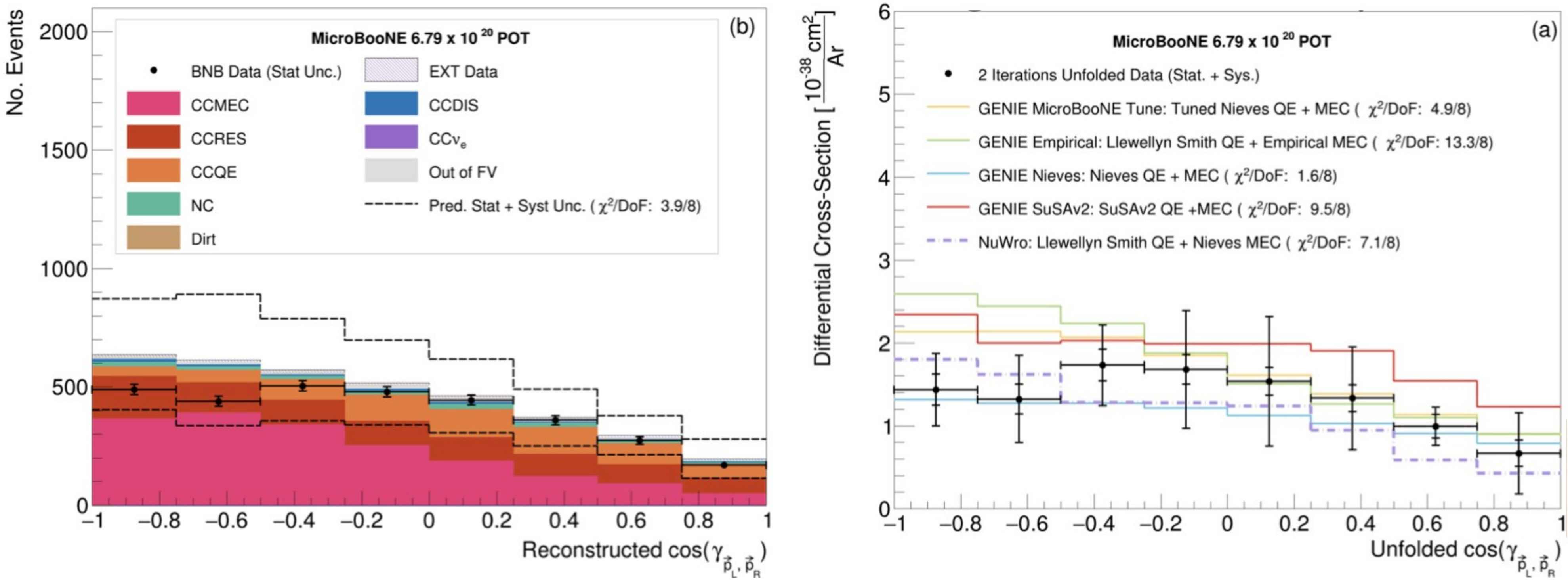


arXiv:2301.03700 , accepted by PRL

arXiv:2301.03706, accepted by PRD

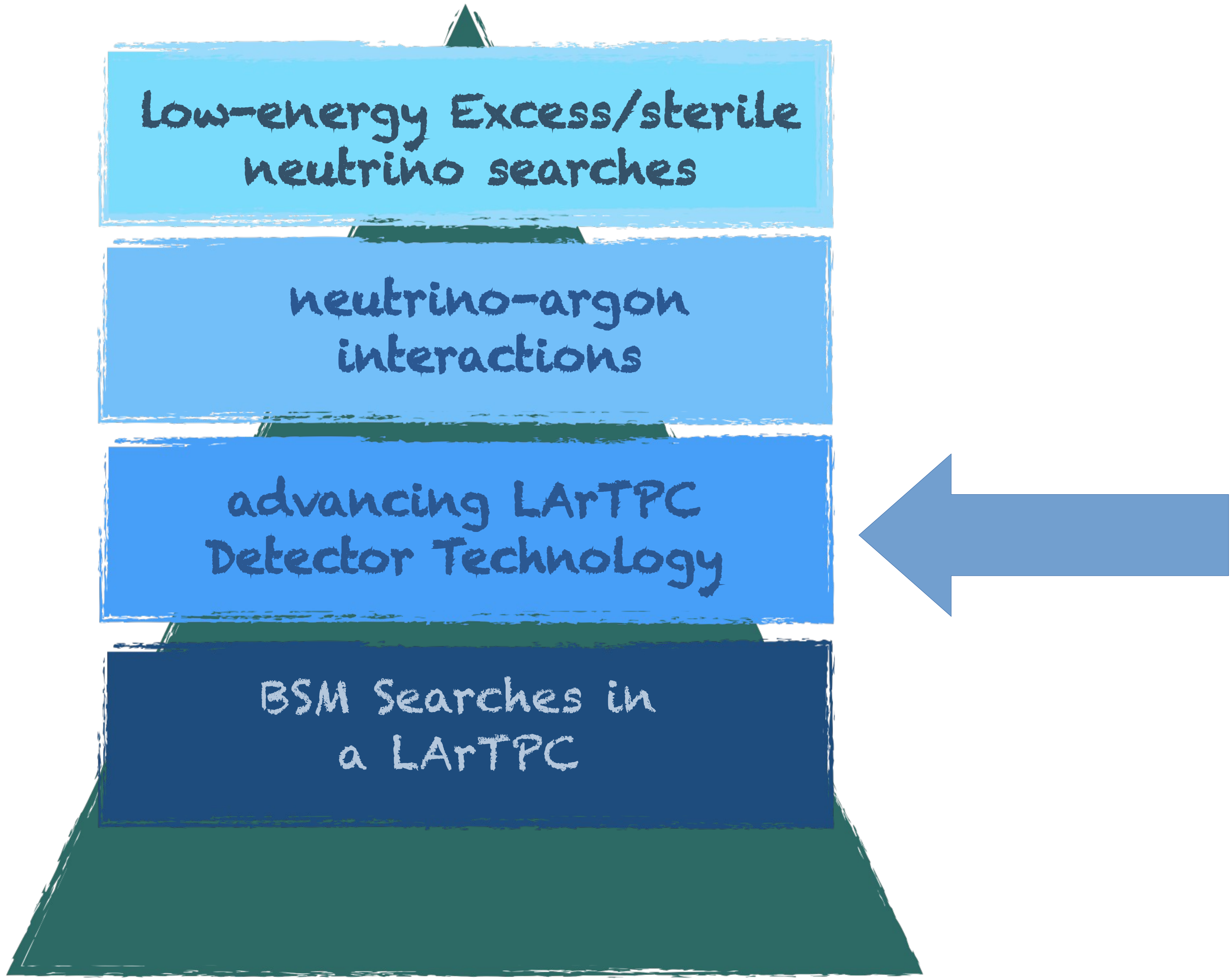
MicroBooNE Multi-Proton Measurement: 1μ2p0π

- Event selections mostly selects MEC (Meson Exchange Current) events
- Model tension when angle between the two protons is small



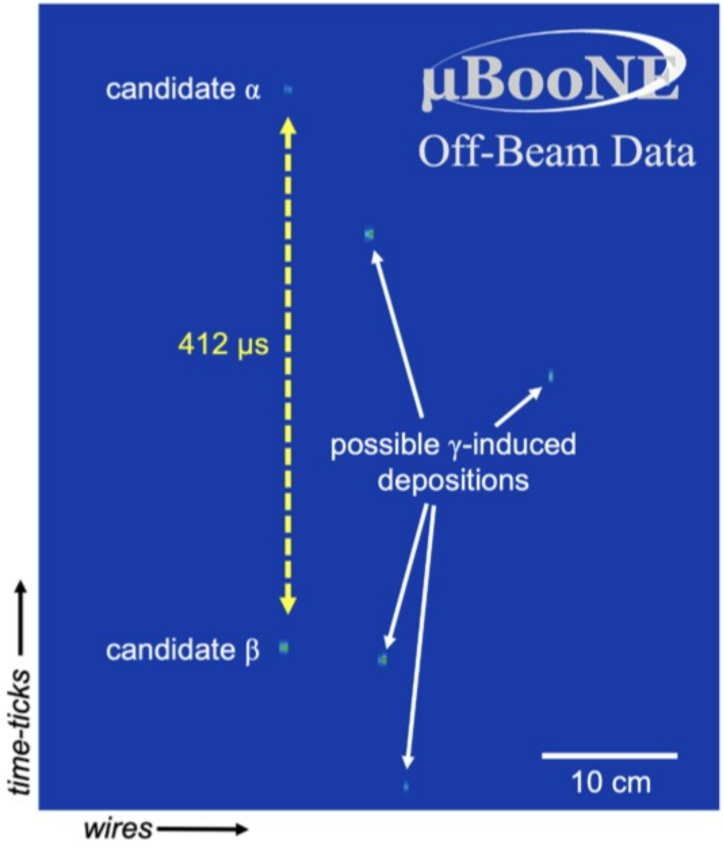
arXiv:2211.03734

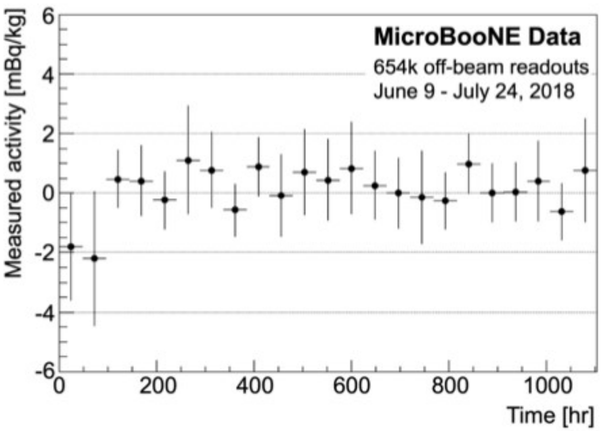
MicroBooNE Physics Program



Advancing LArTPCs

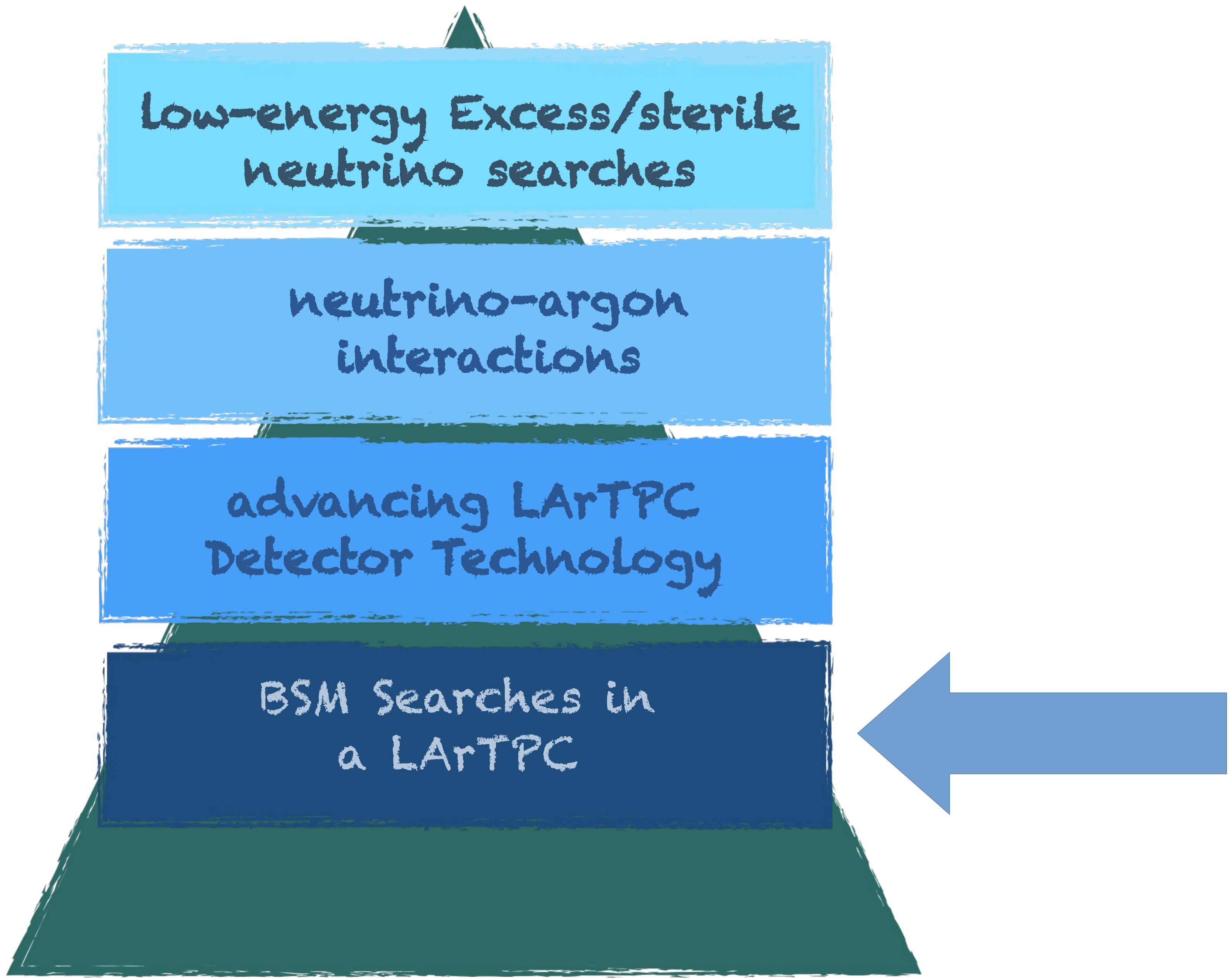
- Latest papers include achieving ns timing resolution (Phys. Rev. D 108, 052010) and investigating the presence of Rn daughters in a sizable LArTPC
  - Demonstrating particle calorimetry and identification at the lowest energies recorded in a single-phase neutrino LArTPC, as important input to MeV-scale astrophysics searches in future DUNE





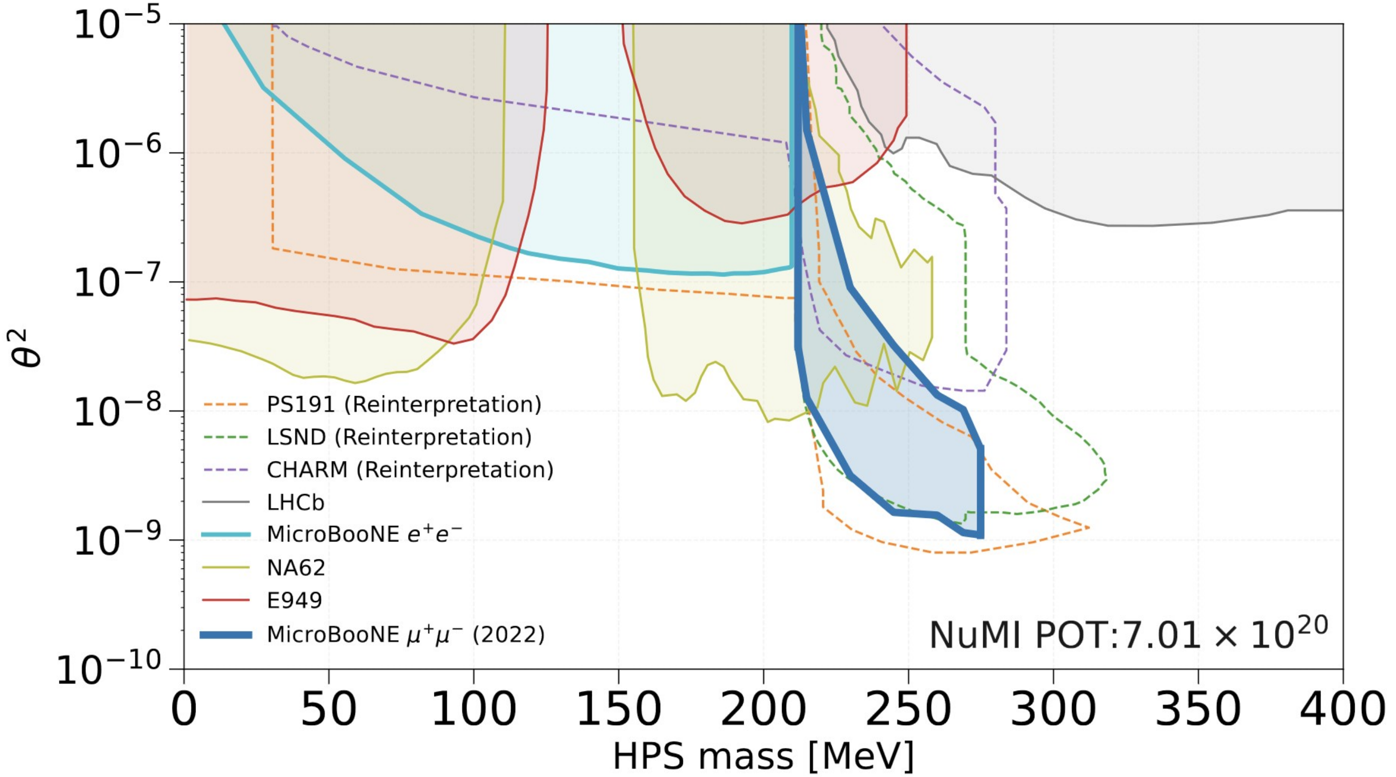
arXiv:2307.03102v1

MicroBooNE Physics Program



BSM Searches

- Many published and on-going BSM studies in MicroBooNE from HNL (Heavy Neutral Leptons), HPS (Higgs Portal Scalar) to Dark Trident, and Millicharged searches: Phys. Rev. D 101, 052001 (2020), Phys. Rev. Lett. 127, 151803 (2021), Phys. Rev. Lett. 129, 111803, Phys. Rev. Lett. 121, 241801
- Many of these scenarios predict overlapping e+e- final states which can be used for the LEE searches

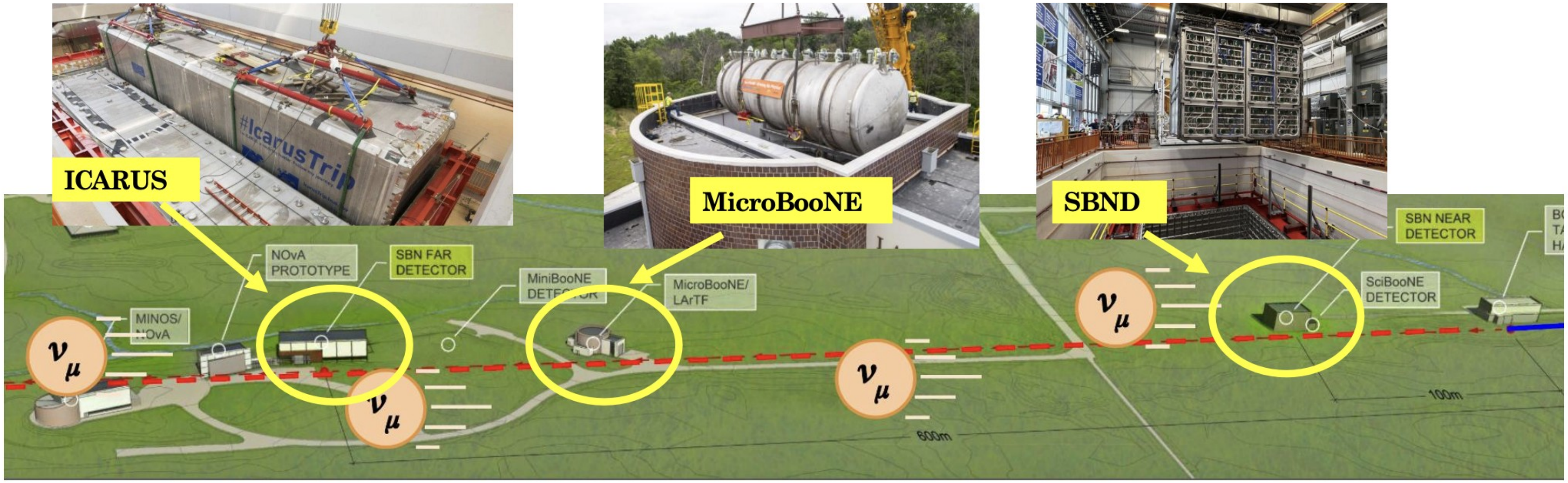


Phys. Rev. D 106, 092006 (2022)

Summary

- Leveraging the most extensive ν-Ar dataset available, MicroBooNE is providing vital input to upcoming precision oscillation experiment, DUNE, in the context of ν-Ar interaction cross sections, LArTPC detector advancements, and rare/exotic physics searches

- The flagship MicroBooNE analyses aimed at resolving the MiniBooNE LEE anomaly so far rules out NC $\Delta \rightarrow N\gamma$ backgrounds and dismisses the notion that electron events from νe entirely account for the MiniBooNE LEE
  - ★ We have only used ~half of the BNB data set so far; stay tuned for results from all BNB data sets as well as combined BNB+NuMI beam!



Additional Slides

Level of Neutrino Interaction Uncertainty Today

T2K https://doi.org/10.1038/s41586-020-2177-0

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

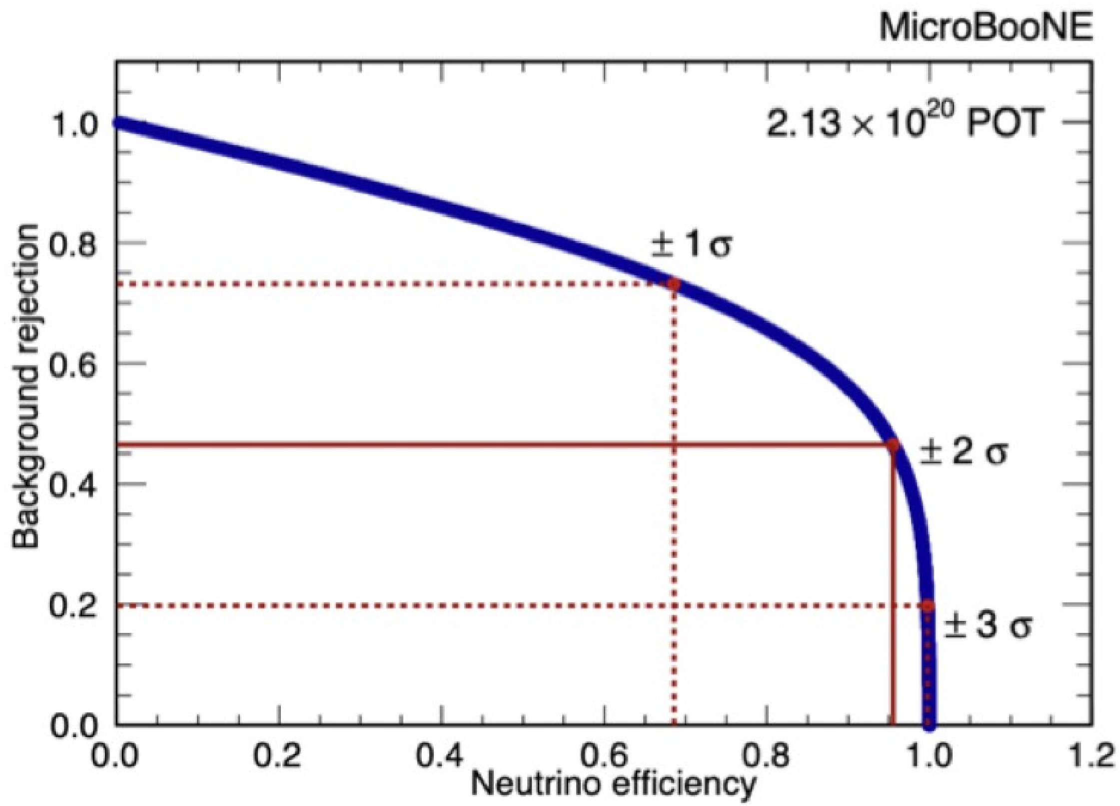
NOvA https://doi.org/10.1103/PhysRevLett.123.151803

Source	ν_e Signal (%)	ν_e Bkg. (%)	$\bar{\nu}_e$ Signal (%)	$\bar{\nu}_e$ Bkg. (%)
Cross-sections	+4.7/-5.8	+3.6/-3.4	+3.2/-4.2	+3.0/-2.9
Detector model	+3.7/-3.9	+1.3/-0.8	+0.6/-0.6	+3.7/-2.6
ND/FD diffs.	+3.4/-3.4	+2.6/-2.9	+4.3/-4.3	+2.8/-2.8
Calibration	+2.1/-3.2	+3.5/-3.9	+1.5/-1.7	+2.9/-0.5
Others	+1.6/-1.6	+1.5/-1.5	+1.4/-1.2	+1.0/-1.0
Total	+7.4/-8.5	+5.6/-6.2	+5.8/-6.4	+6.3/-4.9

- From existing experiments, T2K and NOvA, the dominant sources of uncertainties are cross sections/neutrino interactions

Advancing LArTPCs – $\mathcal{O}$(1 ns) Timing Resolution

- Pioneering achievement in demonstrating $\mathcal{O}$(1 ns) timing resolution
  - Introduces a novel cosmic-rejection technique for distinguishing neutrino interactions arriving in approximately 2 ns pulses in the BNB



Phys. Rev. D 108, 052010

Neutrino Interactions

- We expect a specific range of energies in neutrino experiments:
  - Each experiment will be sensitive to a specific interaction type and a specific set of nuclear effects, affecting what we see in the detectors

charged current interaction channels