The Fermilab Short-Baseline Neutrino Experiments

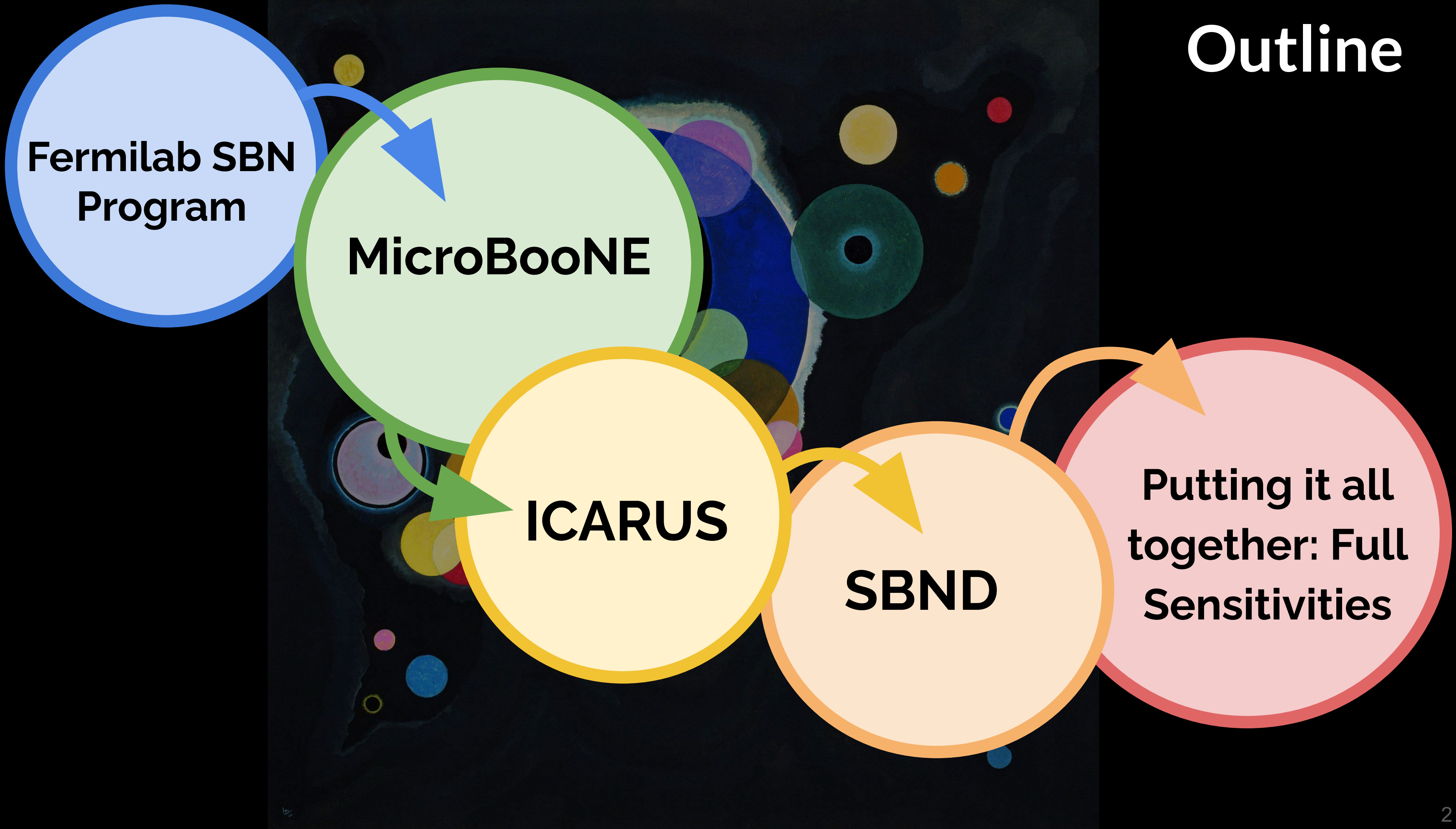
Mark Ross-Lonergan

On behalf of MicroBooNE, SBND and ICARUS

NuFact 2022, Snowbird Resort, Utah

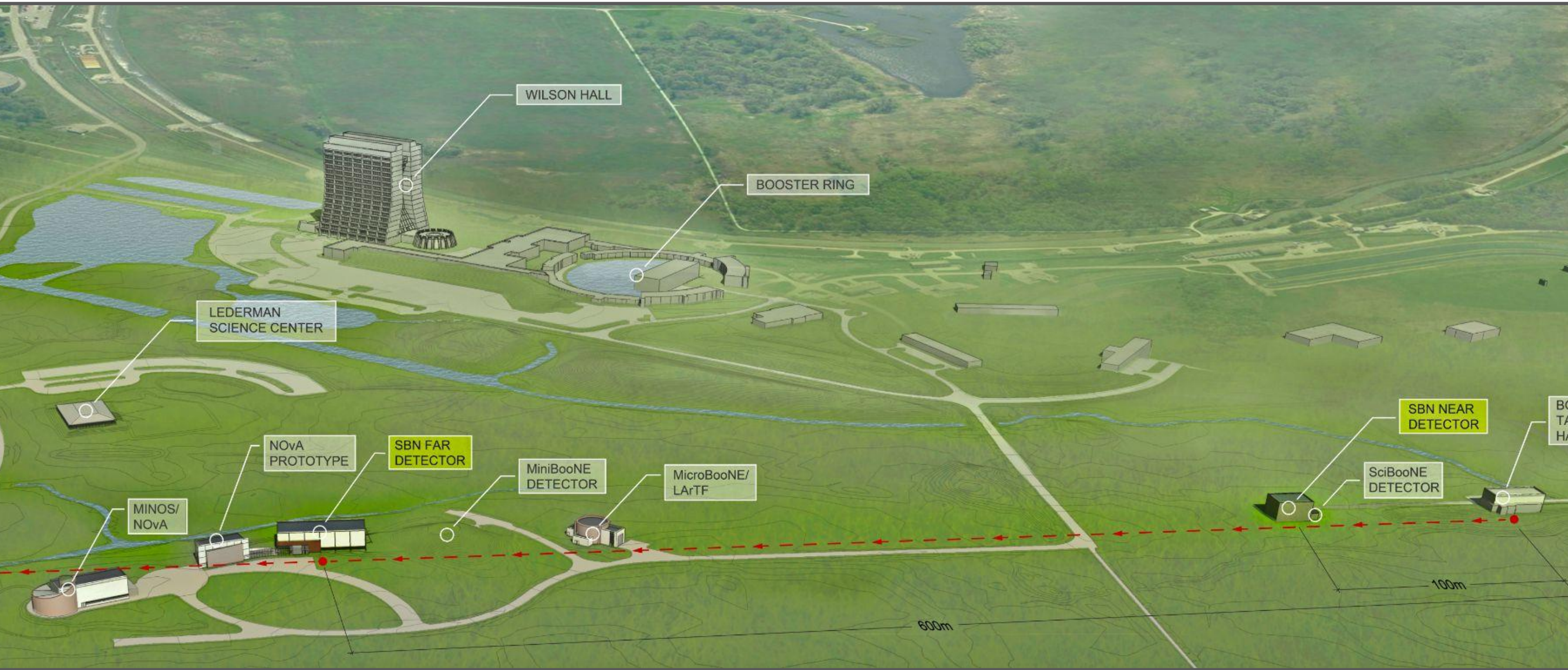
August 4th 2022

Outline

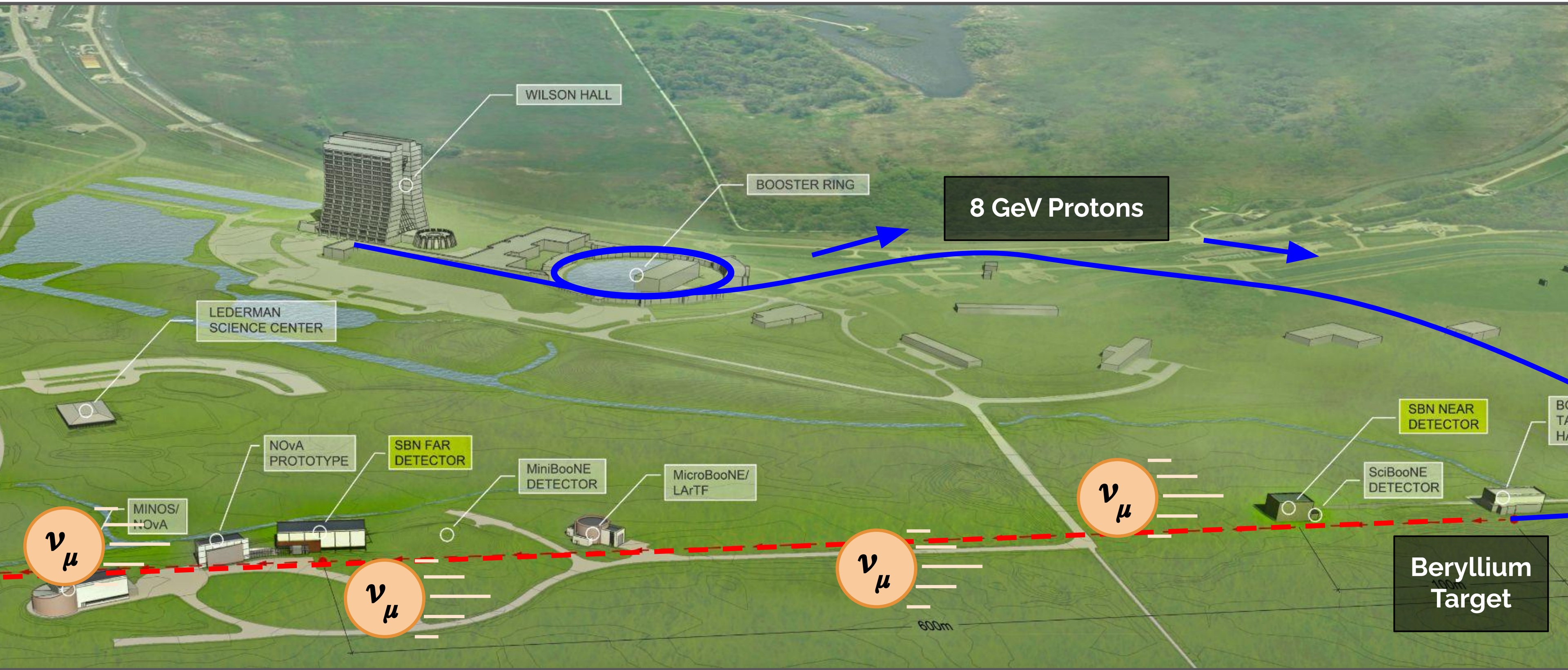


Fermilab SBN Program
MicroBooNE
ICARUS
SBND
Putting it all together: Full Sensitivities

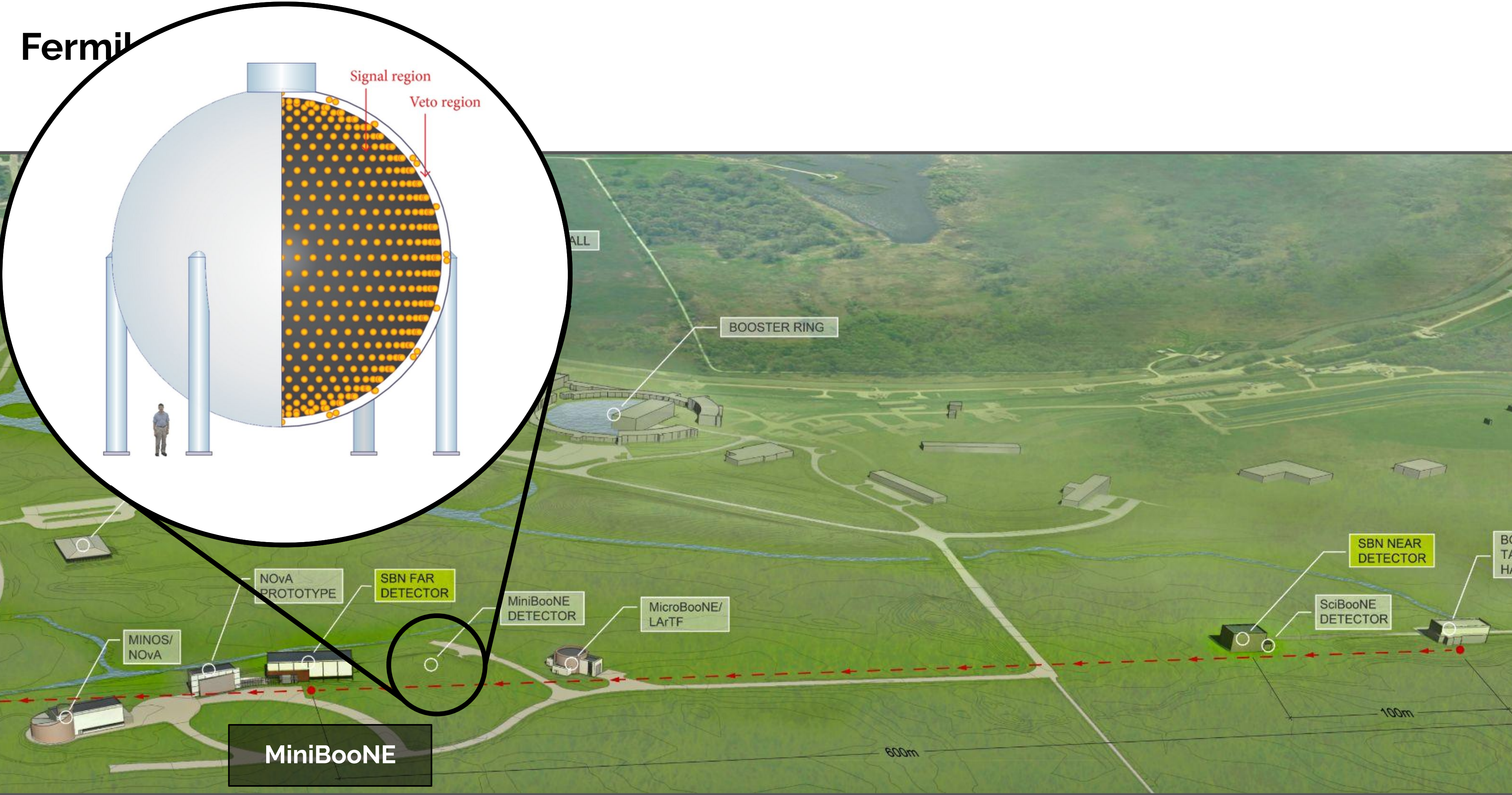
Fermilab


WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
100m
600m

Booster Neutrino Beam (BNB)

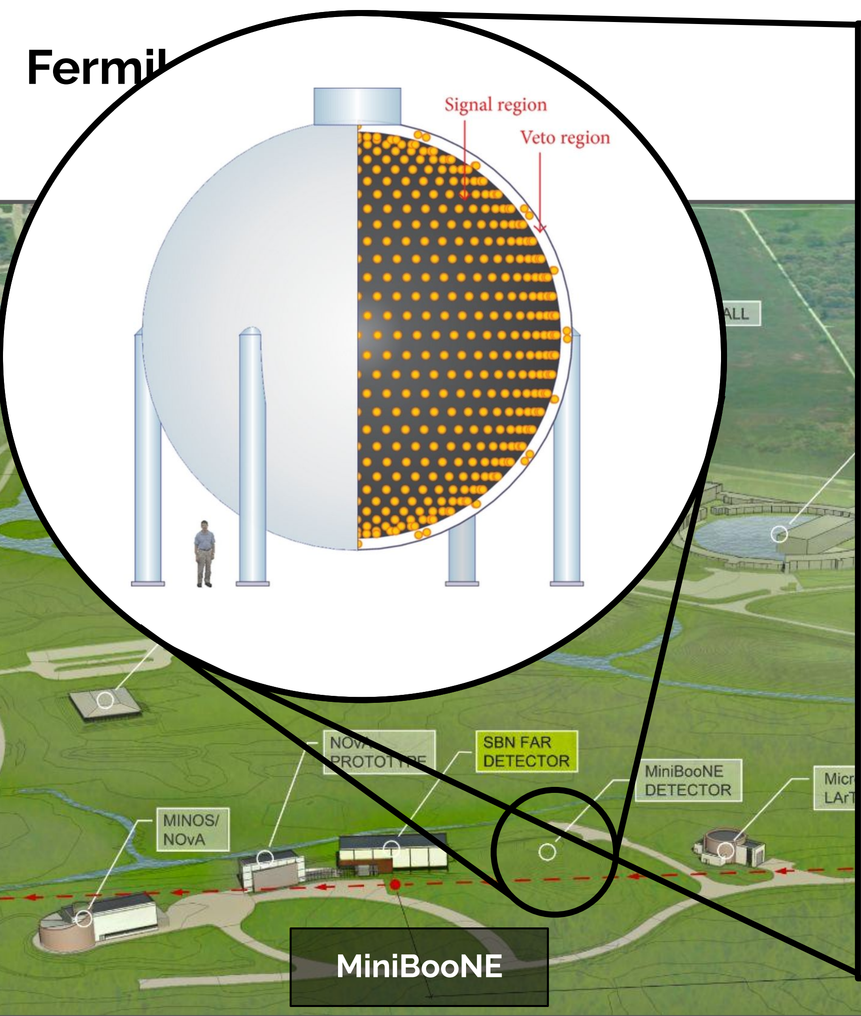


Fermil



Signal region
Veto region
BOOSTER RING
SBN NEAR DETECTOR
SciBooNE DETECTOR
MicroBooNE/ LArTF
MiniBooNE DETECTOR
SBN FAR DETECTOR
NOvA PROTOTYPE
MINOS/ NOvA
MiniBooNE
600m
100m

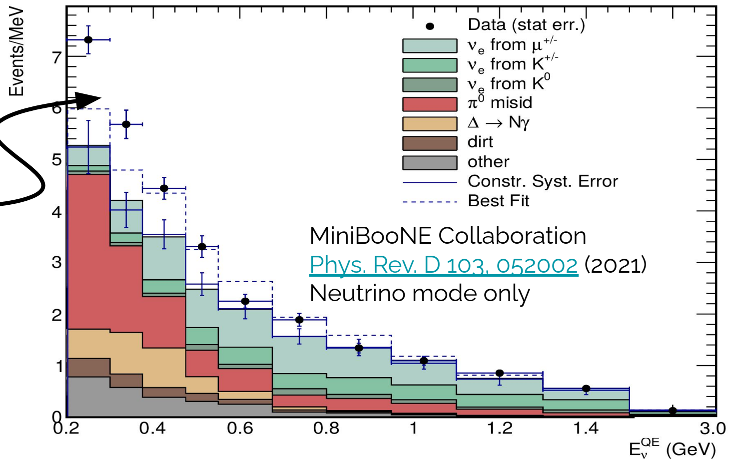
Fermil



MiniBooNE **"Low-Energy Excess"** Anomaly

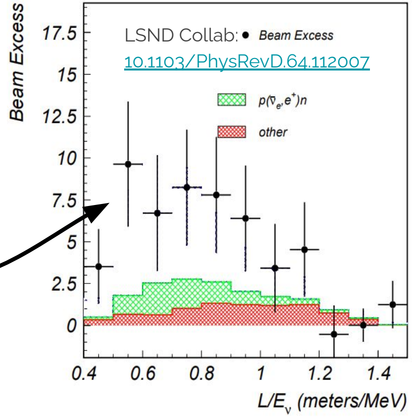
An excess of **electron-like** **events!**

Significance ~4.8σ



Further evidence for possible neutrino **oscillations at O(1 eV²)** mass-splittings, **alongside LSND**

Significance ~3.8σ

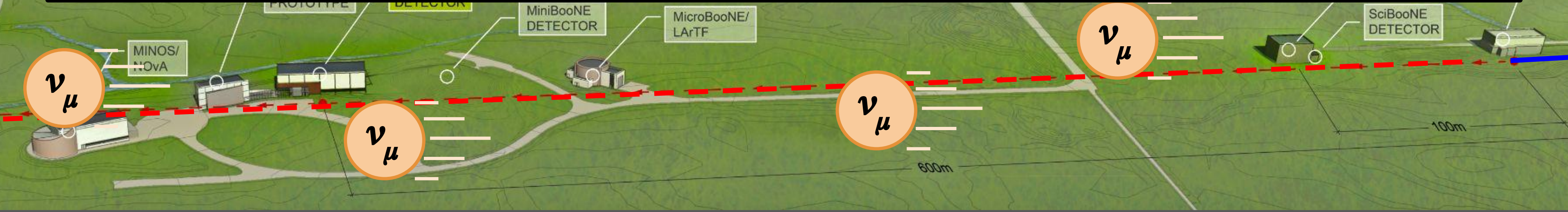


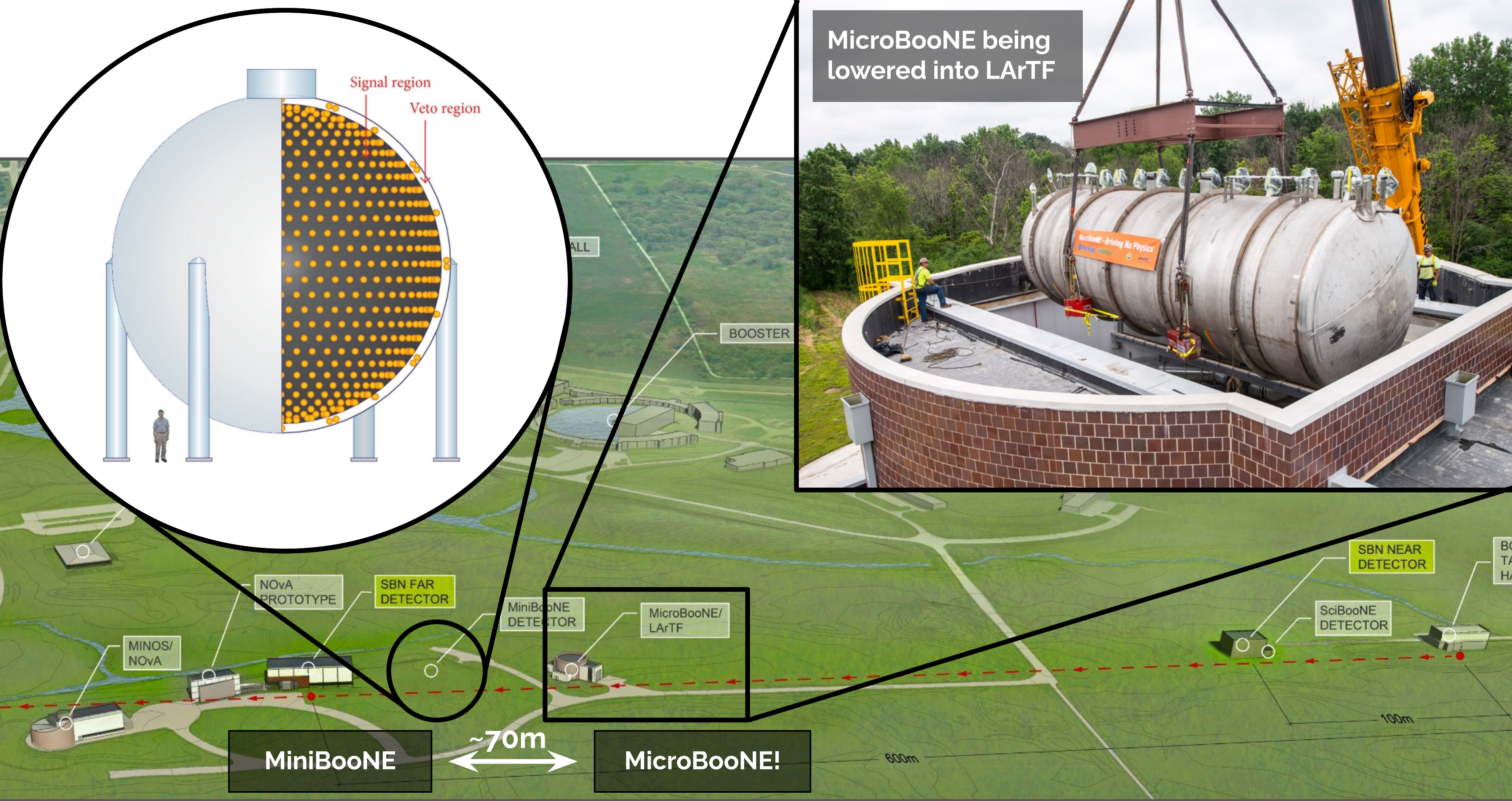
What's going on at short baselines!?!

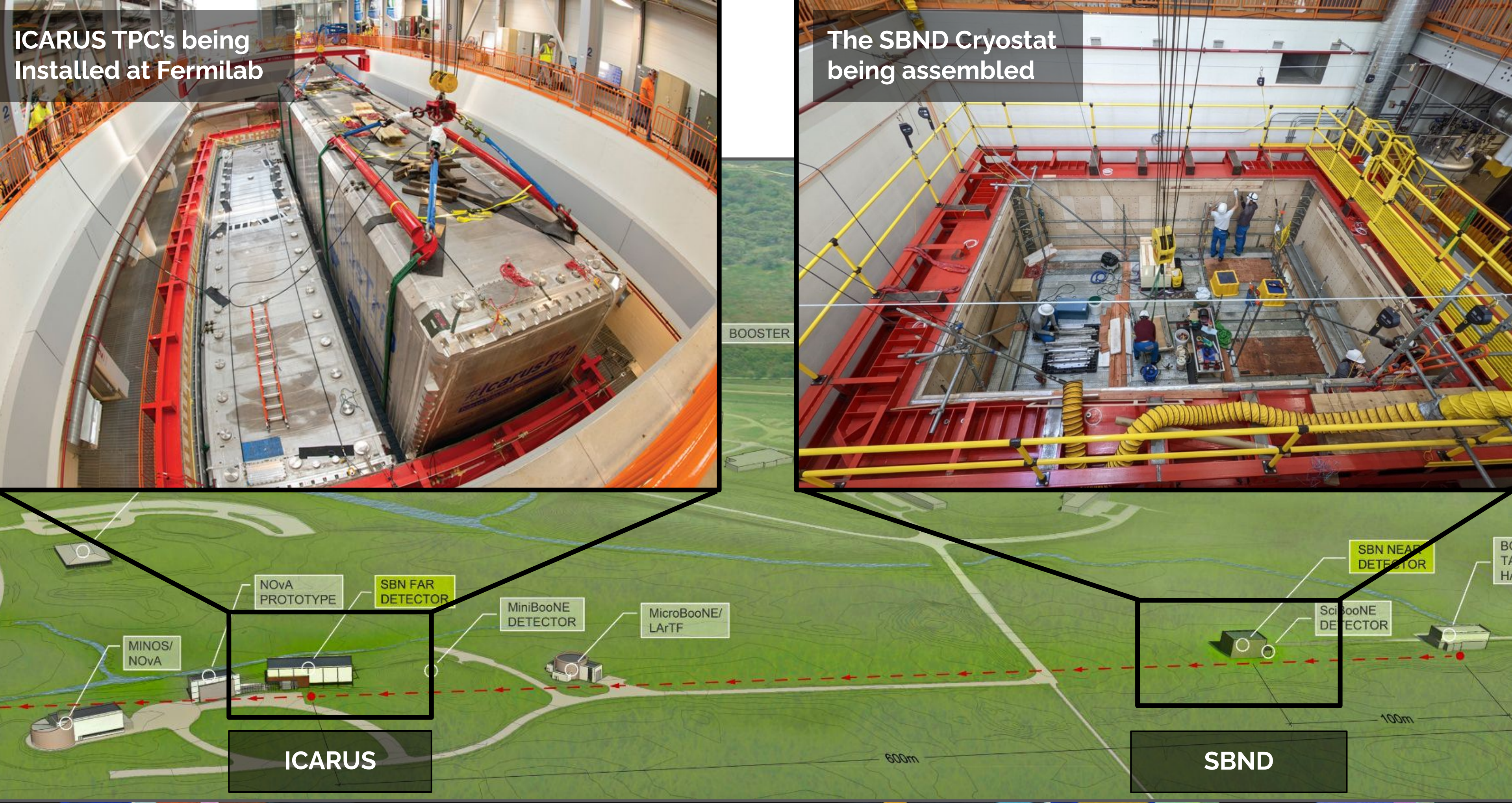
The **Driving Science** of the Fermilab Short-Baseline Neutrino Program

- Investigate the source(s) of the **Low-Energy Excess** observed by MiniBooNE
- Definitive **discovery** or **exclusion** of **~1 eV sterile neutrinos**, a region motivated by LSND and MiniBooNE
- Study **neutrino-Argon interactions** with high precision, eventually using millions of ν_μ events and tens of thousands of ν_e events
- Cast a wide net in a broader search for exotic **Beyond Standard Model Physics**

[SBN proposal arxiv:1503.01520 (2015)]




Signal region
Veto region
MicroBooNE being lowered into LArTF
BOOSTER
MINOS/ NOvA
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
SciBooNE DETECTOR
SBN NEAR DETECTOR
100m
600m
MiniBooNE
~70m
MicroBooNE!


ICARUS TPC's being Installed at Fermilab
The SBND Cryostat being assembled
BOOSTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
100m
600m
ICARUS
SBND

Short-Baseline Neutrino Program: Three detectors in the same Neutrino Beam, using same Liquid Argon Time Projection Chamber (**LArTPC**) detector technology.

ICARUS-T600 Factsheet

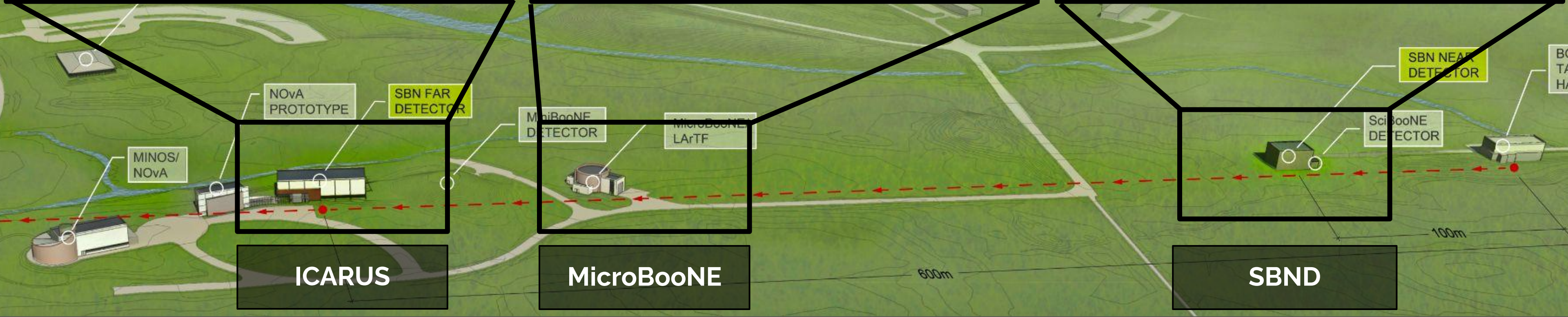
BNB Baseline: **600m**
Dimensions: 2x (19.6 x 3.6 x 3.9 m^3)
Total LAr mass 760 ton
Active LAr mass 476 ton
-75 kV high voltage
1.5 m drift distance
53,248 Wires in TPC
360 8" PMTs

MicroBooNE Factsheet

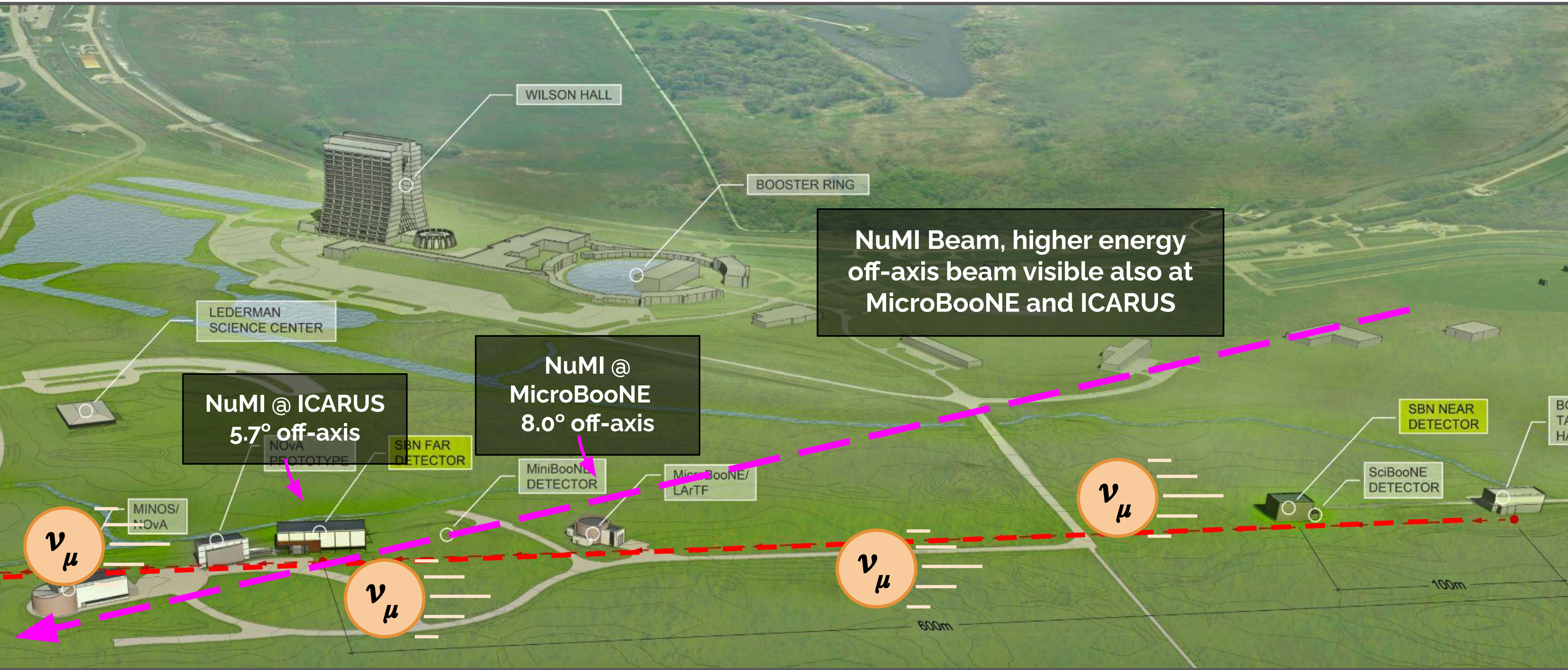
BNB **Baseline: 470m**
Dimensions: (2.33 x 2.56 x 10.37 m^3)
Total LAr mass 170 ton
Active LAr mass 90 ton
-70kV high voltage
2.5 m drift distance
8,256 Wires in TPC
32 8" PMTs

SBND Factsheet

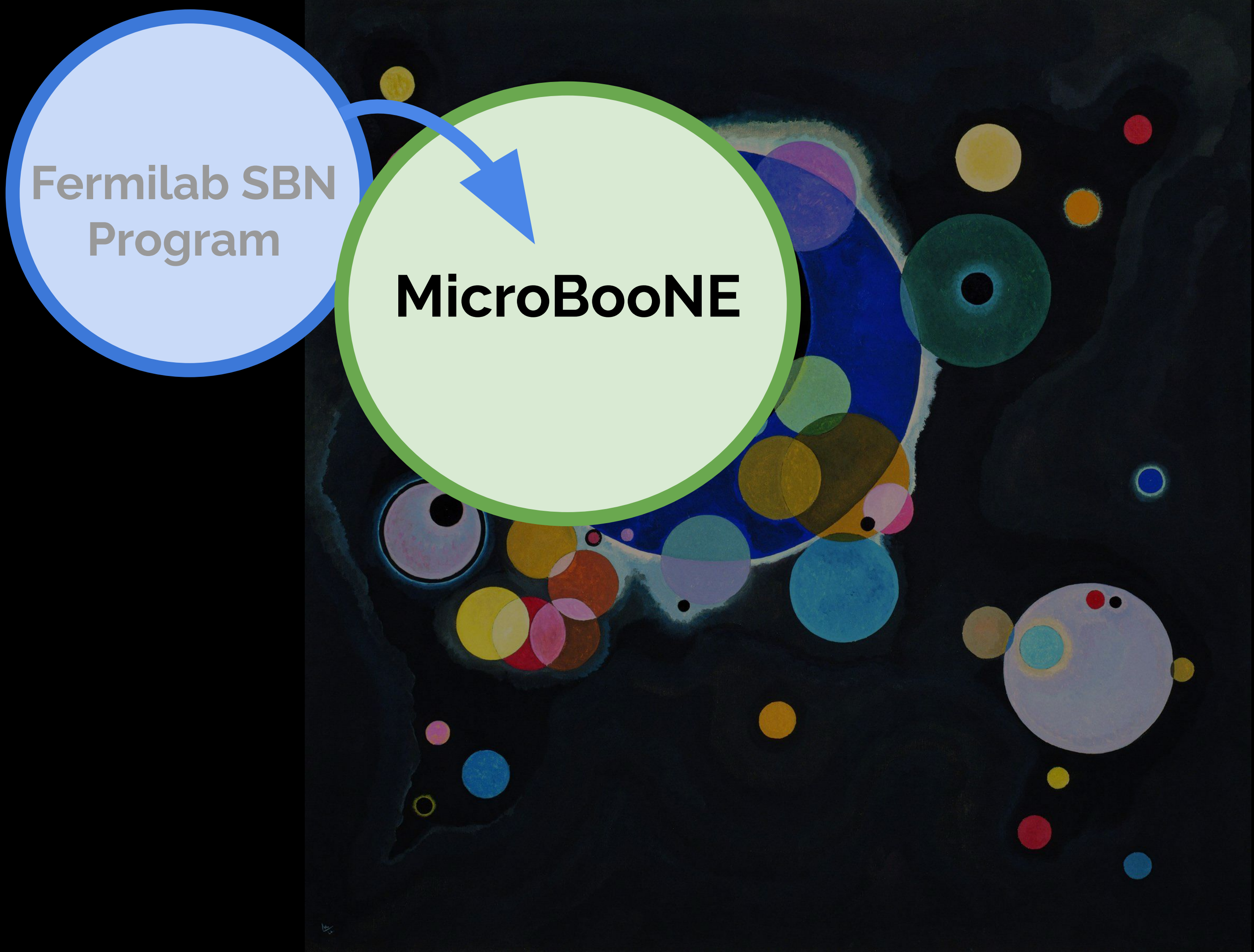
BNB Baseline: **110m**
Dimensions: (4 x 4 x 5 m^3)
Total LAr mass 270 ton
Active LAr mass 112 ton
-100 kV high voltage
2m drift distance
11,263 Wires in TPC
120 8" PMTs & 192 X-ARAPUCAs



“Same Neutrino Beam**(s)**” : Booster Neutrino Beam (BNB)
& NuMI Neutrino Beam (Neutrinos from the Main Injector)

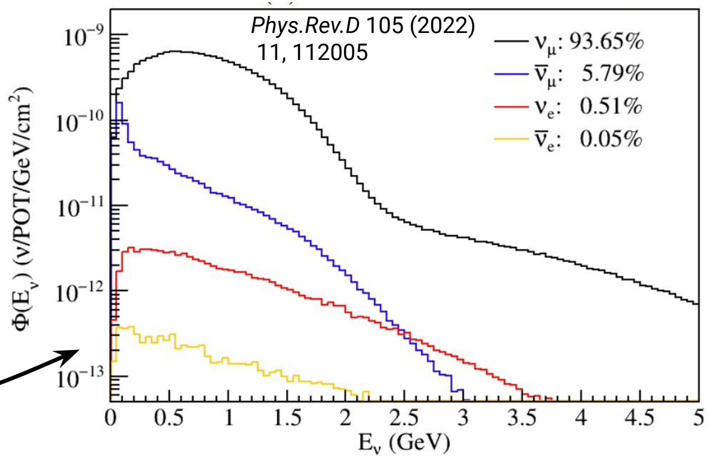


Outline

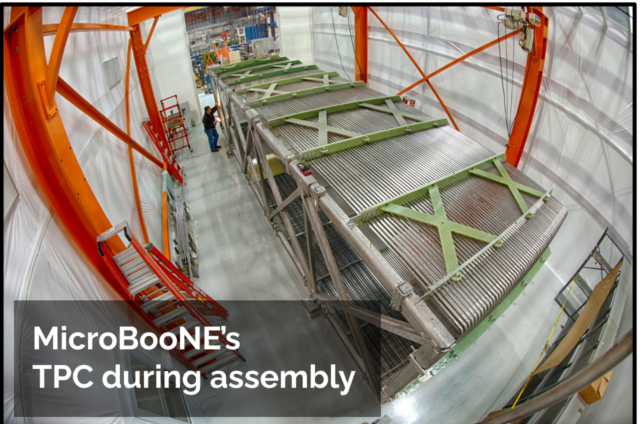


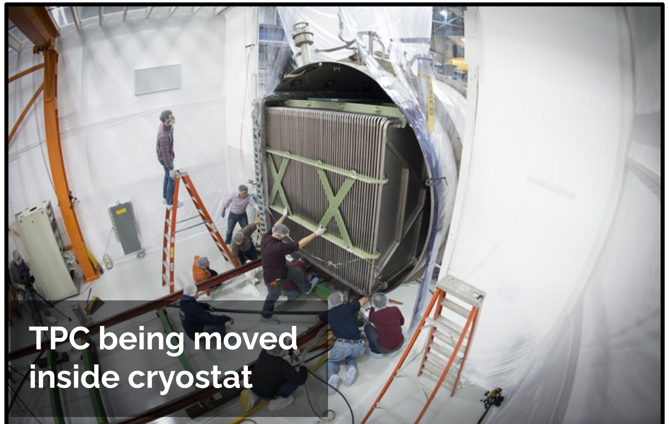
The MicroBooNE Experiment

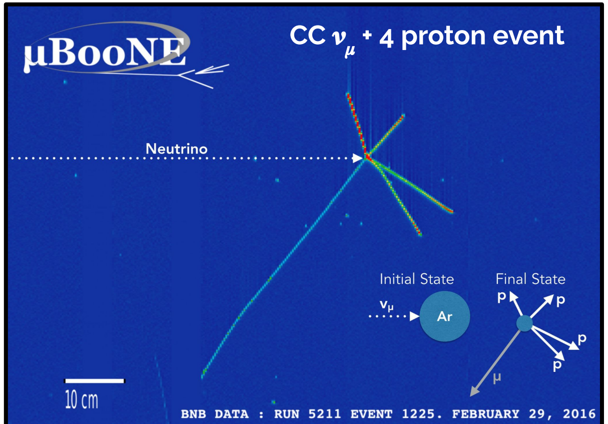
MicroBooNE is a 170 metric ton LArTPC, sitting ~470m downstream in the BNB that collected data from **2015 to 2020**, amassing the **largest sample of neutrino interactions on argon in the world**



The BNB flux at MicroBooNE is overwhelming $\boldsymbol{\nu_\mu}$ **&** $\boldsymbol{\bar{\nu}_\mu}$ (99.54%) with a **mean energy of ~0.8 GeV**


MicroBooNE's TPC during assembly


TPC being moved inside cryostat



μBooNE MicroBooNE Publications

2017 | 2018 | 2019 | 2020 | 2021 | 2022

49 papers published since 2017, with more than **70 additional** public-notes to share with wider community as we learnt

Accelerating Growth?

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 in 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 ve 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
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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
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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
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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-pion pairs in the MicroBooNE detector
Reconstruction and Measurement of 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
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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

MicroBooNE Publications

μBooNE

8 papers focused on exotic **BSM** physics and on flagship **Low-Energy Excess searches**

10 papers improving our understanding of neutrino cross-sections on Argon, with ~ 30 more analysis on the way!

Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector
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Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
Design and Construction of the MicroBooNE Detector

31 on **vital LArTPC hardware and software R&D,** dessiminiting pioneering info for DUNE and SBN program

MicroBooNE's Goals

Focus on MicroBooNE's recent results here

Flagship **Low-Energy Excess searches** and other Exotic **BSM physics**

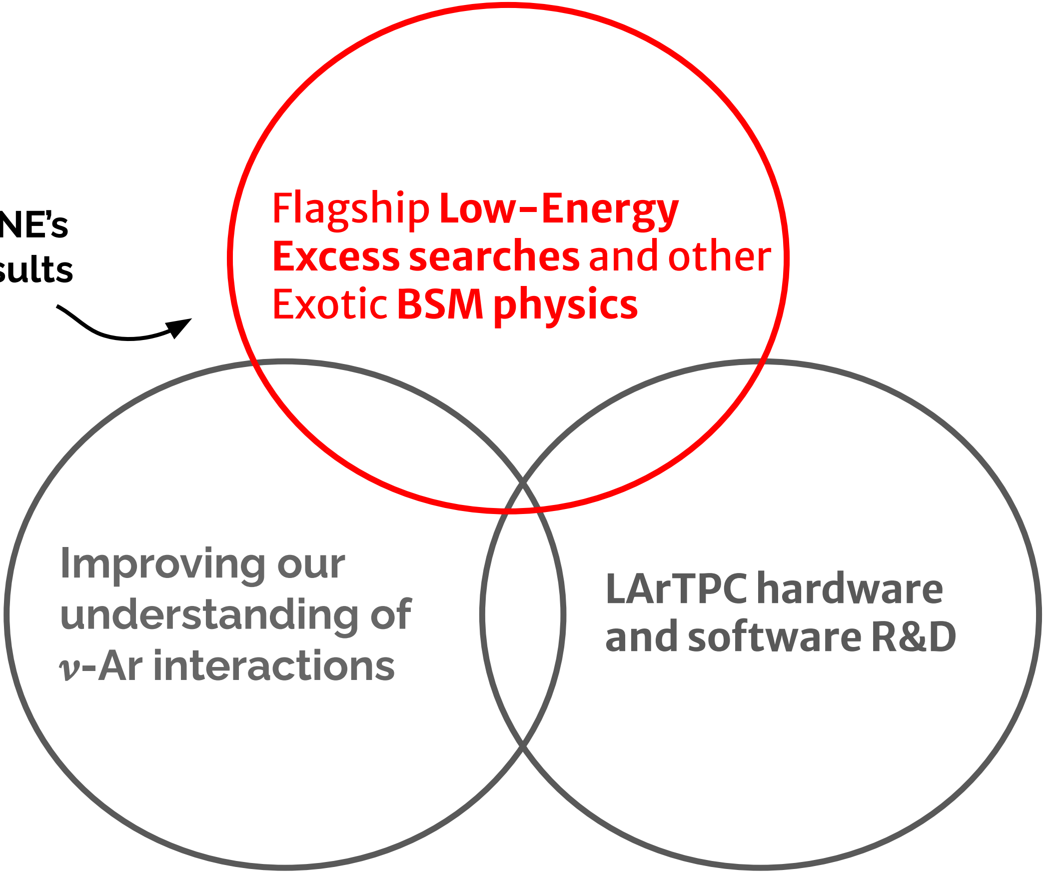
Improving our understanding of ν-Ar interactions

LArTPC hardware and software R&D

For more info on one aspect, energy reconstruction and calibration, see **Wanwei Wu's** talk <u>Aug 5th, 2:56pm, in WG6</u>

MicroBooNE's Goals

Focus on MicroBooNE's recent results here



What can LArTPCs do that MiniBooNE couldn't?

Electrons or Photons?

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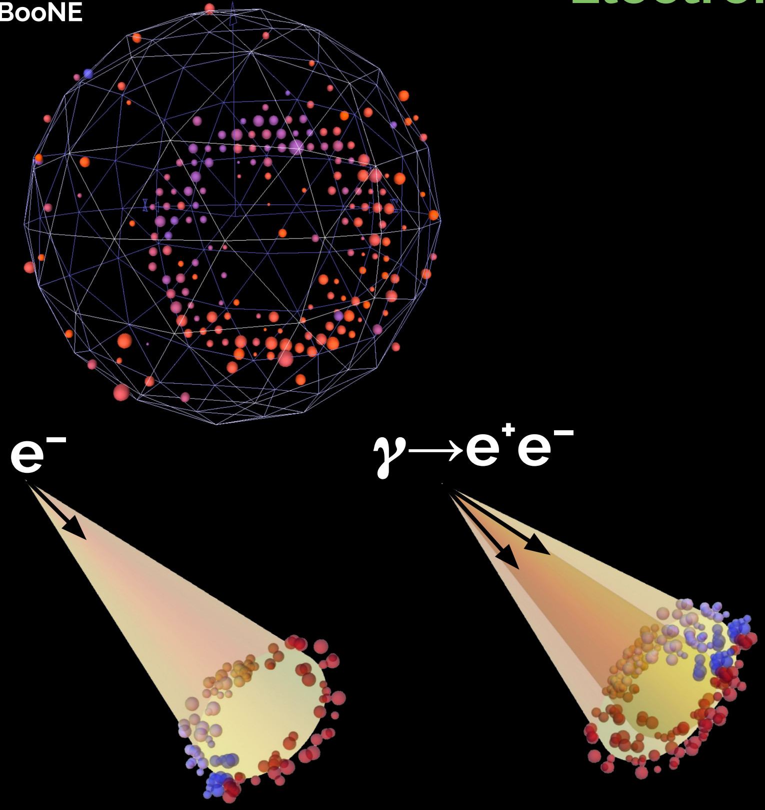
Electron Cherenkov ring event in MiniBooNE

Electrons or **Photons?**



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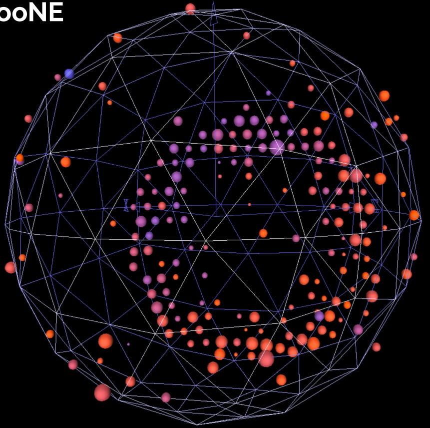
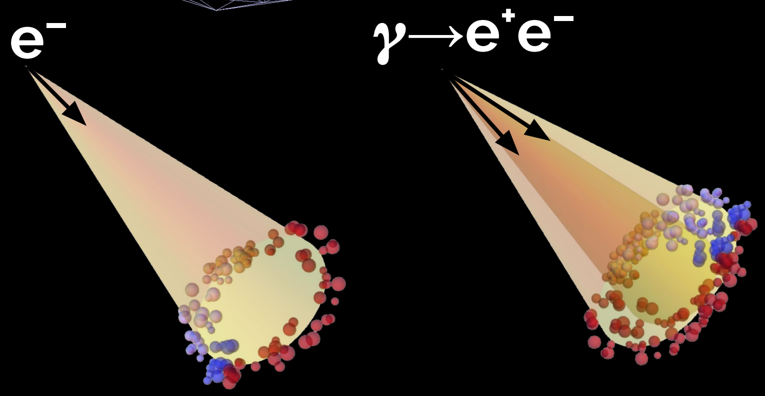
Electron Cherenkov ring event in MiniBooNE

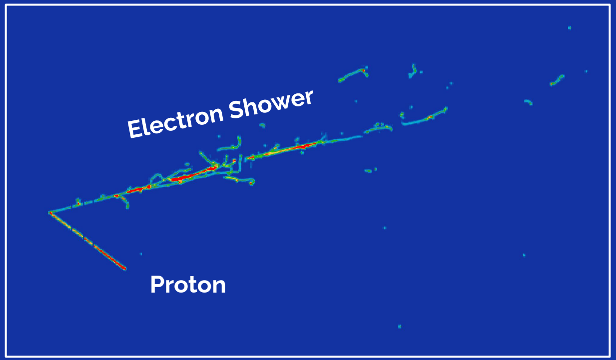


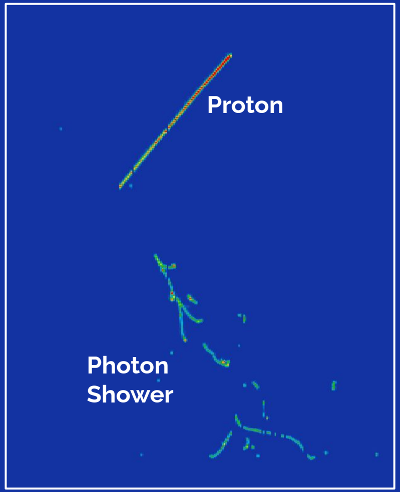


Electrons or Photons?

LArTPC's give us **fully active calorimeter** alongside **high-resolution tracking**

CC ν_e + 1 proton candidate data event





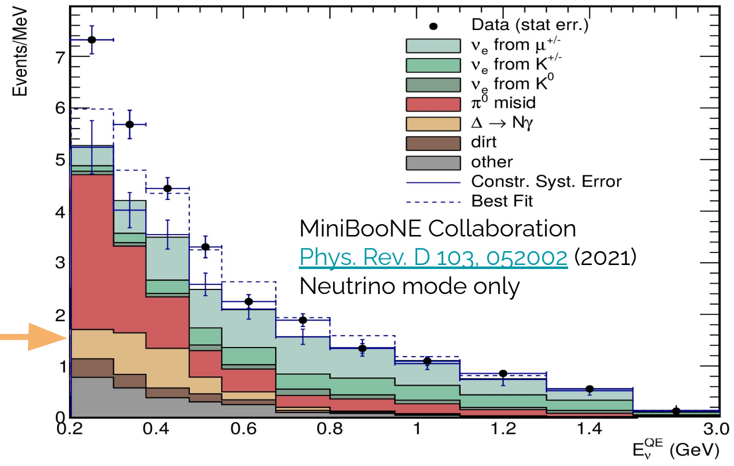
NC single photon + 1 proton candidate data event

Allows for strong **photon ↔ electron separation** and particle identification across whole SBN program!

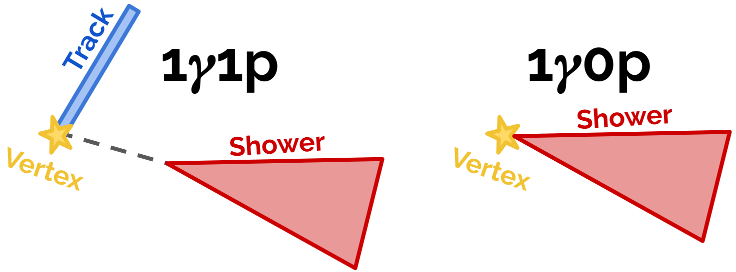
MicroBooNE's First Low-Energy Excess (Photon) Results

MicroBooNE's first search for a photon excess targeted an extremely rare standard model process, **Neutral Current Δ radiative decay (Δ→Nγ)**.

- This process has never been observed in the neutrino sector before
- Previous experimental limits from T2K at O(1) GeV energies were two orders of magnitude higher than prediction
- Only needs to be **~3.18 times higher than predicted** in order to **explain the MiniBooNE anomaly**

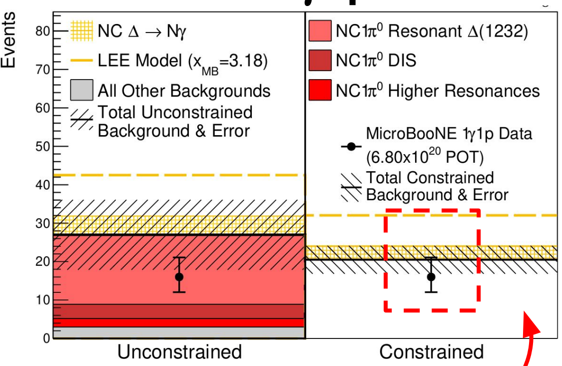


Perform a search in MicroBooNE for single photons from **NC Δ→Nγ** both with and without an associated proton:

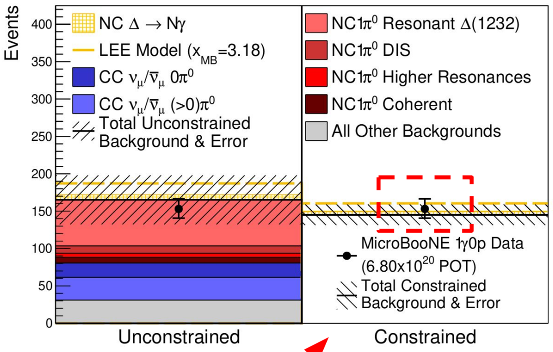


MicroBooNE's First Low-Energy Excess (Photon) Results

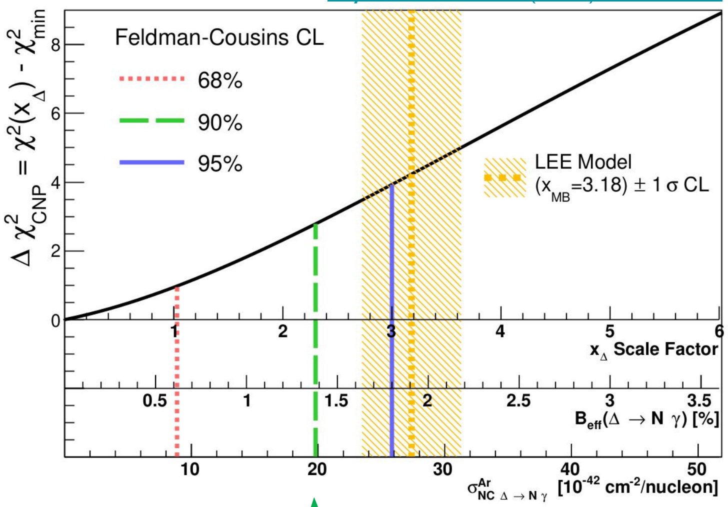
1γ1p



1γ0p



[Phys.Rev.Lett. 128 (2022) 11, 111801](https://doi.org/10.1103/PhysRevLett.128.111801)



No excess was observed

This result disfavors NC $\Delta \to N\gamma$ backgrounds as a sole source of the MiniBooNE excess at **94.8% C.L**

For details of this search and more, see
Kathryn Sutton's Aug 5th, 4:10pm in WG5

Resulting bound

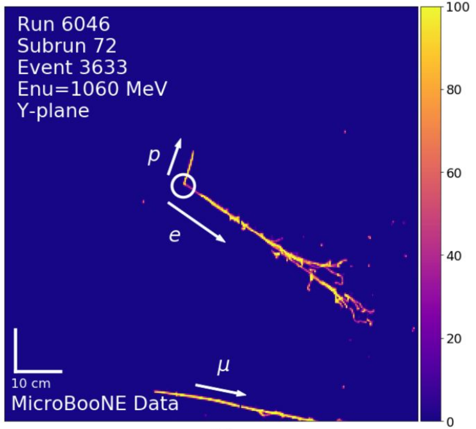
$$\sigma^{Ar}_{\Delta\to N\gamma} < 19.8 \times 10^{-42}\ [\mathrm{cm}^{-2}/\mathrm{nucleon}],\ \text{at } 90\%\ \mathrm{CL}$$

MicroBooNE's First Low-Energy Excess (Electron) Results

Three independent searches targeting **different final states** each with **different novel reconstruction** approaches developed in MicroBooNE.

Exclusive 2-body charged-current quasi-elastic (CCQE) ν_e scattering. [1e1p CCQE]

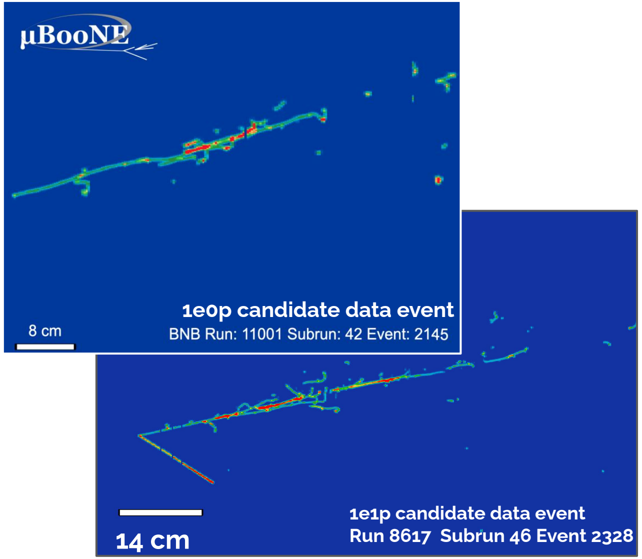
Using image based **Deep-Learning** reconstruction



https://doi.org/10.1103/PhysRevD.105.112003

Semi-inclusive ν_e scattering without final state pions. [1eNp0π] and [1e0p0π]

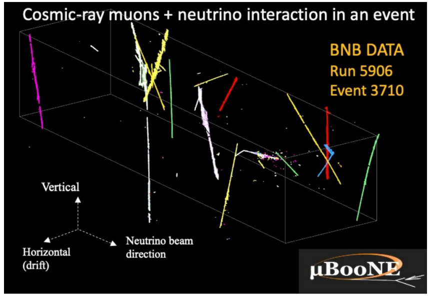
Using **Pandora** reconstruction framework

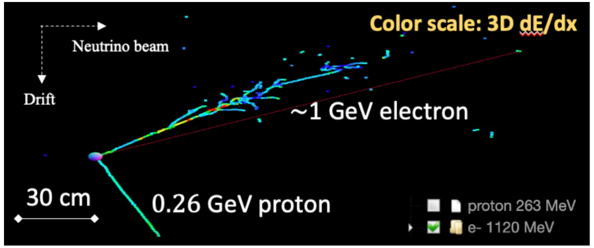


https://doi.org/10.1103/PhysRevD.105.112004

Fully Inclusive ν_e scattering. [1eX]

using **Wire-Cell** Reconstruction framework

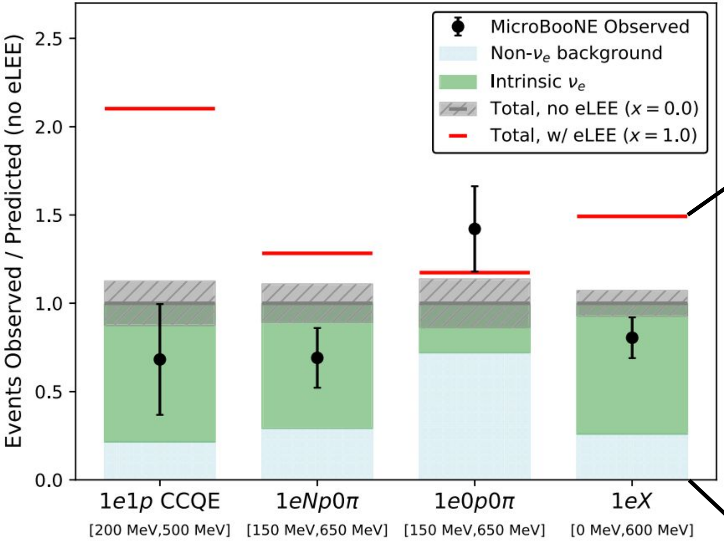




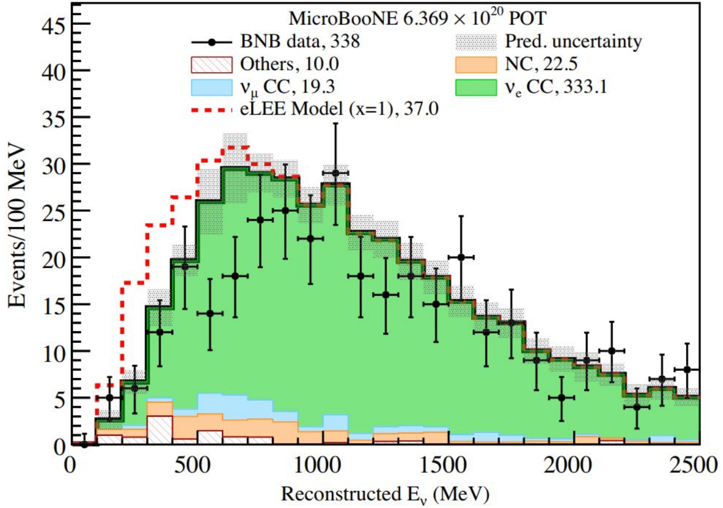
https://doi.org/10.1103/PhysRevD.105.112005

MicroBooNE's First Low-Energy Excess (Electron) Results

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



Inclusive CC ν_e results (1eX)



- Observed ν_e rates are statistically consistent with the predicted background rates
- With exception of the low- ν_e-purity (1e0p0π) channel, a mild deficit of intrinsic ν_e is actually observed

The hypothesis that ν_e events are fully responsible for the median MiniBooNE LEE is **rejected at >3σ** in the **inclusive channel.**

µBooNE

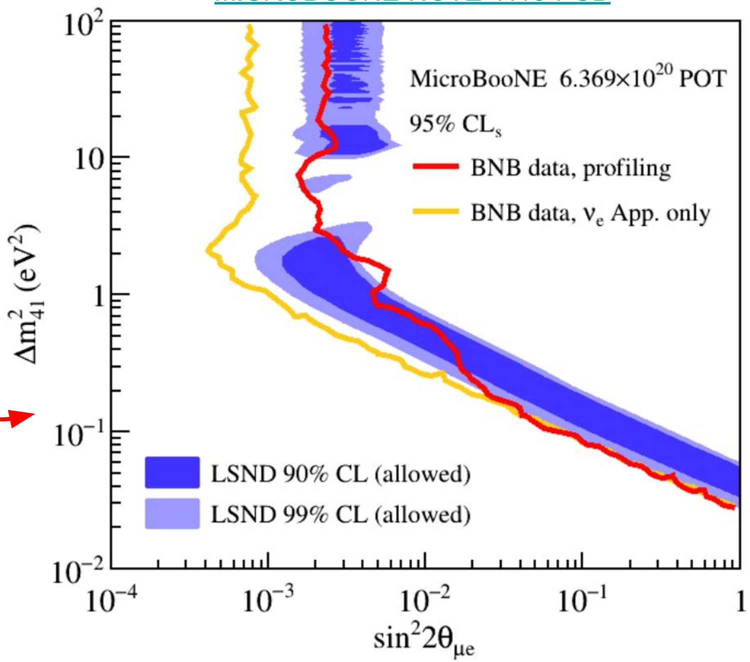
New Constraints on eV-Scale Sterile Neutrinos

These **inclusive CC ν_e** results have subsequently been turned into a **direct bound on eV scale sterile** neutrinos.

As the inclusive CC ν_e selection utilises high statistics CC ν_μ events to help constrain systematics, **a full 3+1 sterile neutrino fit must be performed** in order to fully take into account all possible flavour transitions

- With this **full 3+1 analysis**, part of the LSND allowed region is excluded by the MicroBooNE 95% CL limit
    - Note this is result has profiled over θ_{24} and as such is the most conservative result
- While the ν_e **appearance-only** gives a more stringent limit this is non-physical, as non-zero ν_e appearance strictly requires both ν_e and ν_μ disappearance.

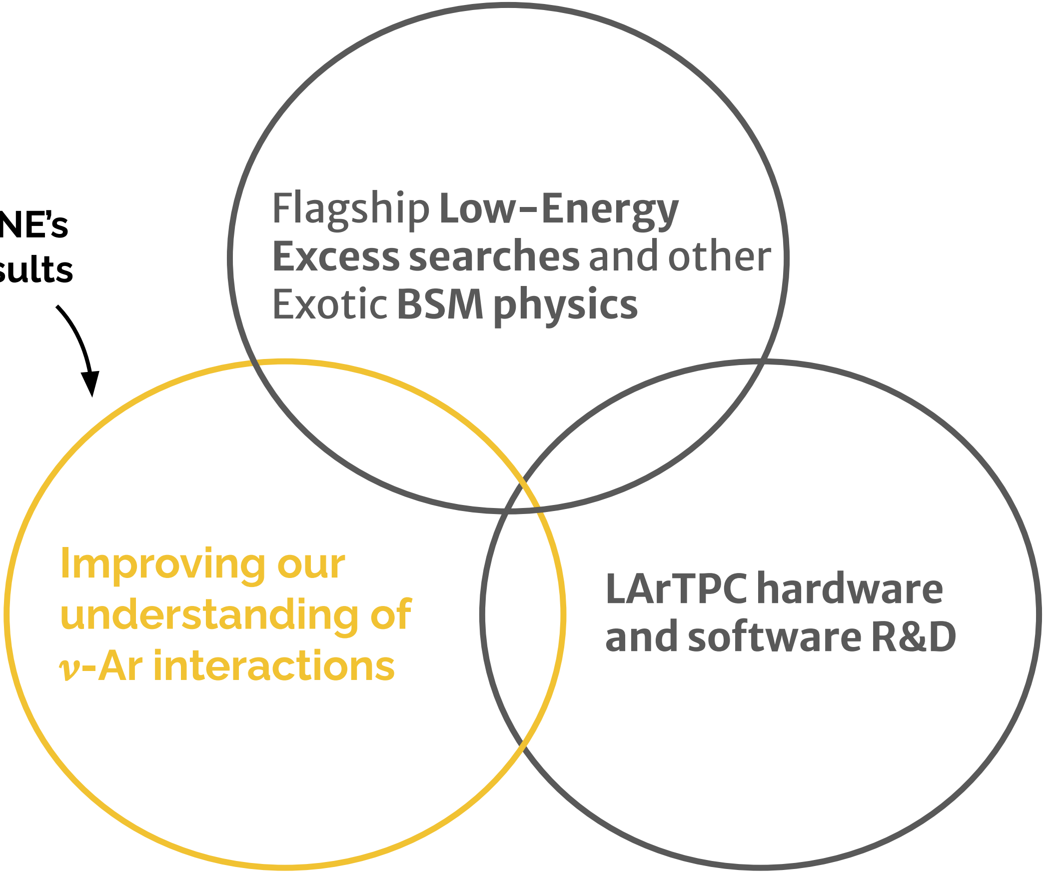
MICROBOONE-NOTE-1116-PUB



For details of this 3+1 sterile neutrino result, alongside all electron searches see **Xiangpan Ji's** talk Aug 2nd, 2:30pm in WG5

MicroBooNE's Goals

Focus on MicroBooNE's recent results here



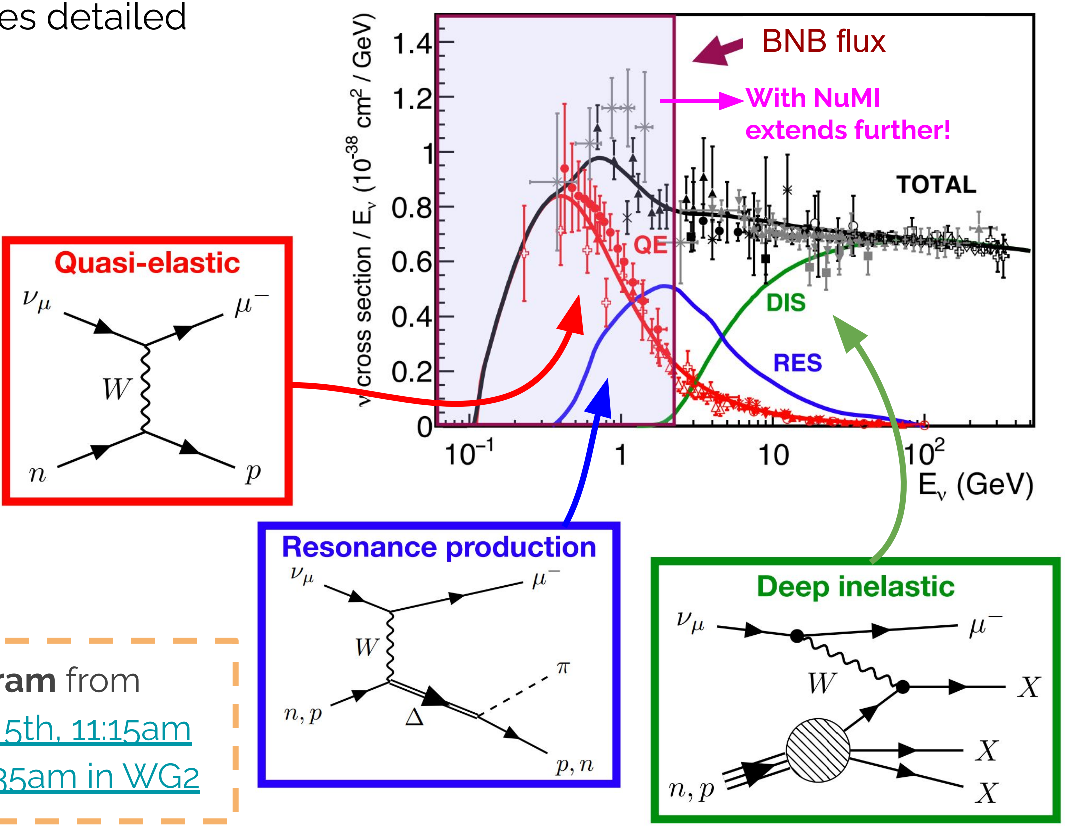
Understanding Neutrino ↔ Argon Interactions

- Any discovery in the neutrino sector requires detailed understanding of neutrino interactions.

- MicroBooNE has developed an **extensive cross-section program** to study **neutrino-argon** interactions using **both BNB and NuMI beams**

- Will highlight only a snapshot of recent results today.

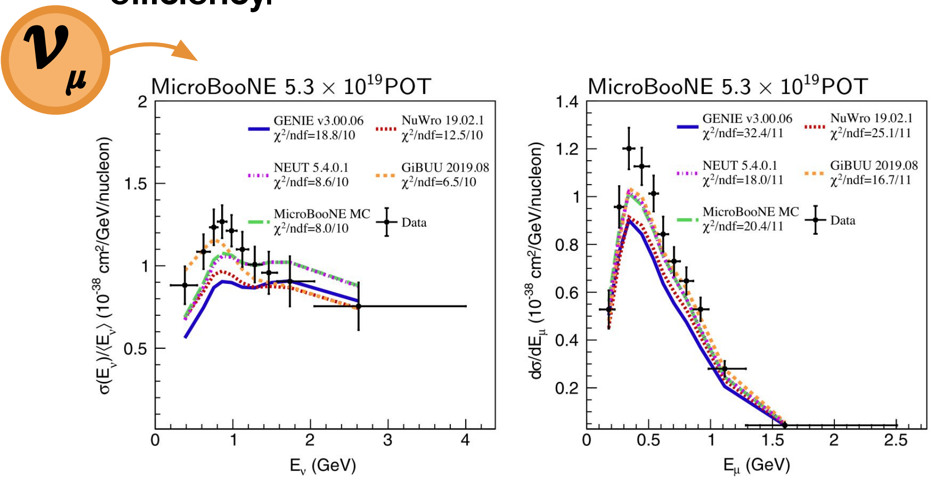
Rev. Mod. Phys. 84, 1307 (2012)



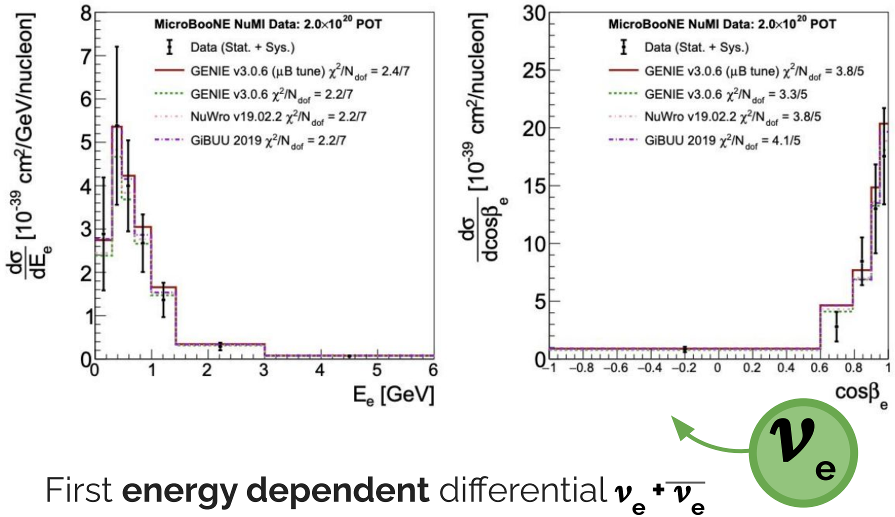
To learn more of the **extensive cross-section program** from MicrobooNE see **Afroditi Papadopoulou's** talk Aug 5th, 11:15am in WG2 , and **Elena Gramellini's** talk on Aug 5th, 11:35am in WG2

Energy-dependent **inclusive charged-current ν_μ cross section** on argon using the BNB beam Phys Rev Lett 128 151801 (2022)

Based on 11,528 selected ν_μ CC interactions with a **high ~92% purity** and **68% selection efficiency.**



Initial results already showing some model discrimination



First **energy dependent** differential $\nu_e + \bar{\nu}_e$ **flux-averaged charged-current inclusive** cross section measurement on argon using NuMI Beam Phys Rev D 104 5, 052002 (2021)

Highest number of ν_e ever recorded on argon and a first ν_e cross-section extraction at O(1 GeV) energies

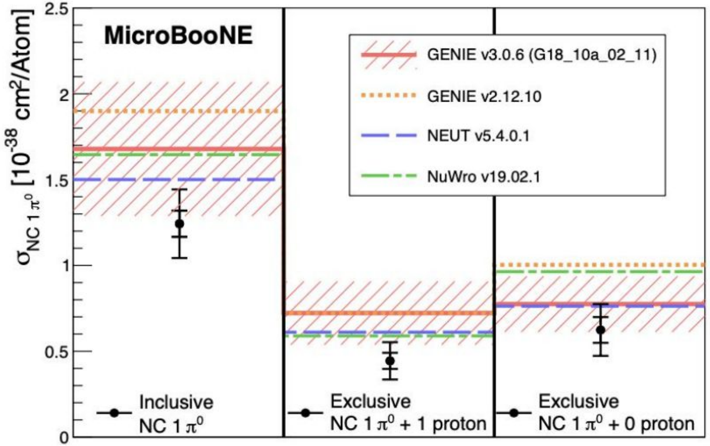
Neutral Current π^0 events produce a large amount of background showers for both CC ν_e analyses as well as many BSM searches.

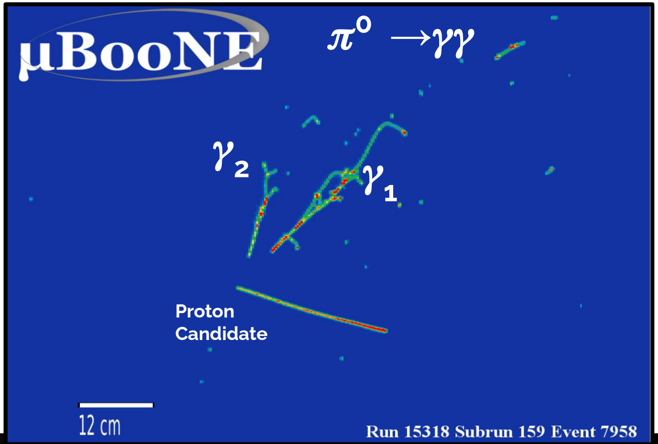
Uncertainties on NC pion production in many neutrino generators are very large.

First NC 1π^0 inclusive on argon with $<E_\nu>$ ~ 1 GeV, and first exclusive NC 1π^0 measurements in the 0p and 1p channels (any target).

A **consistent deficit of NC π^0 events** is observed relative to all neutrino generators predictions.

hep-ex: 2205.07943 (Submitted to PRD)

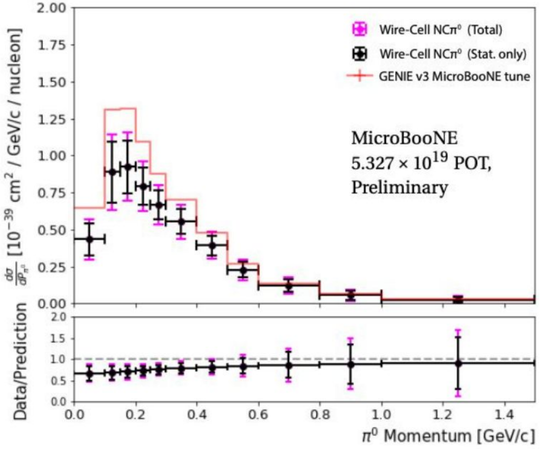




Further work ongoing to extract a inclusive NC (⩾1) π^0 differential cross-section well under way!

Preliminary results with only 5% of total data shows similar deficit

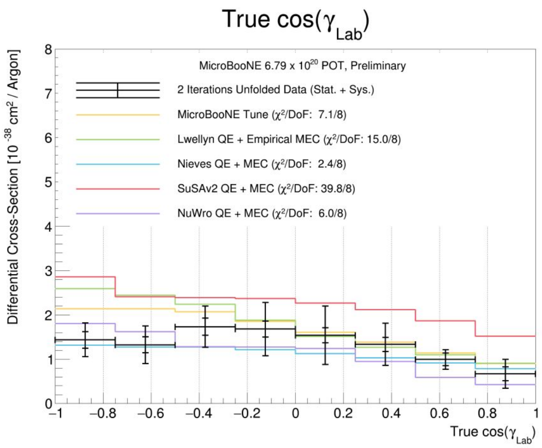
See MICROBOONE-NOTE-1111-PUB



Utilizing the **calorimetric** and **low threshold particle ID capabilities** of LArTPC's one can select and study **precise baryonic final states**

Design analyses to be capable of probing regions of greatest model discrimination power, for a variety of important nuclear models

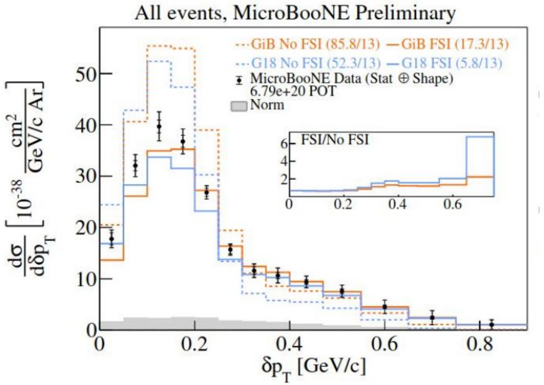
ν_μ CC + 2 proton + 0 π



First neutrino-argon cross sections for an exclusive 2-proton final state.

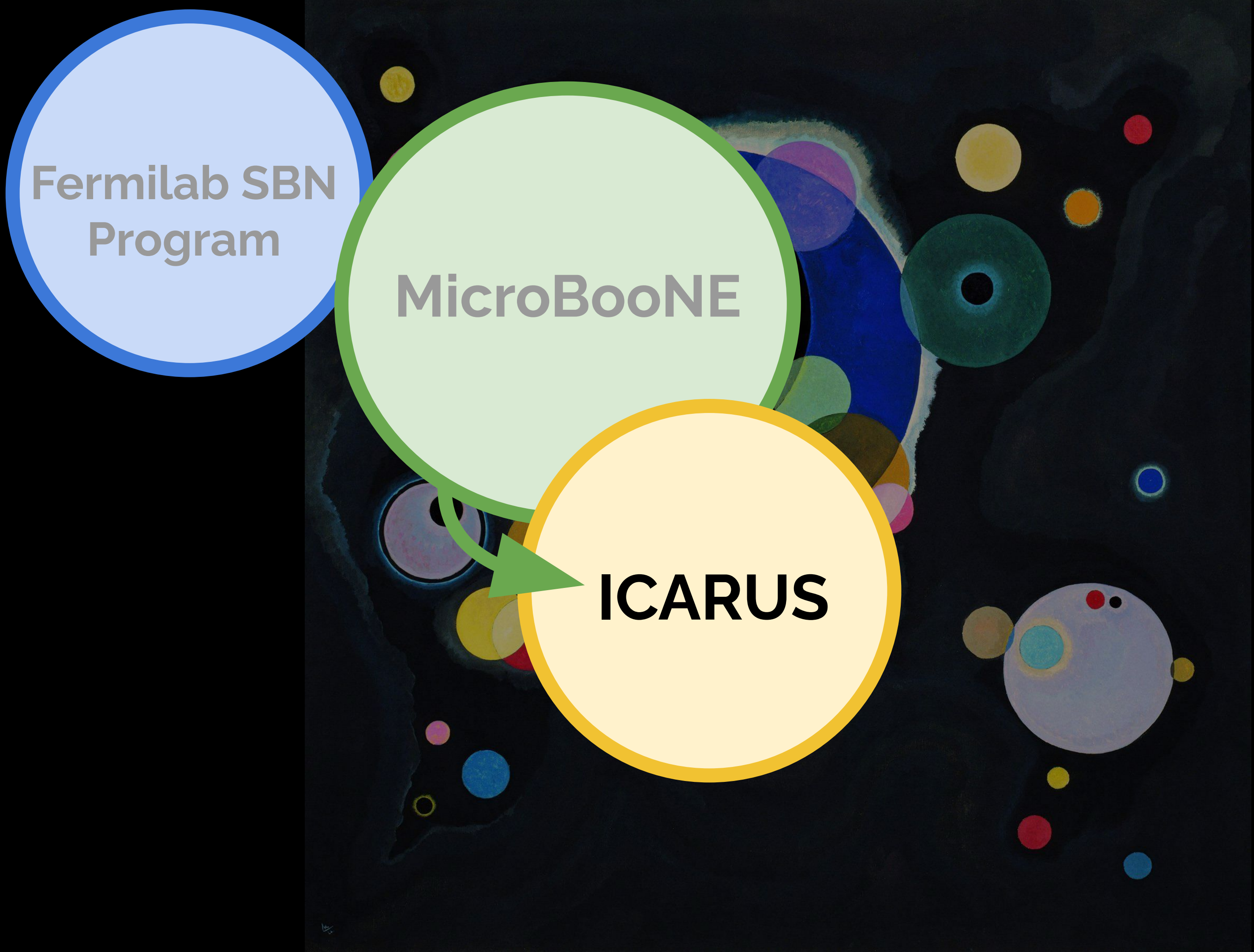
Sensitive to **MEC modelling and 2p2h effects** in contemporary neutrino generators
MICROBOONE-NOTE-1117-PUB

ν_μ CC + 1 proton + 0 π (TKI)



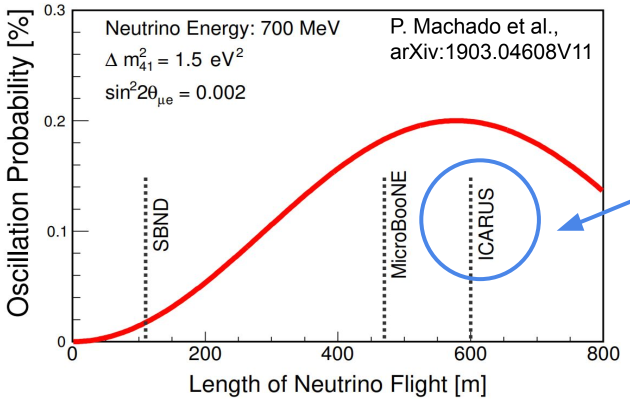
Extract first cross-section using Transverse Kinematic Imbalance variables on argon
Sensitive to initial **nucleon motion & proton FSI modeling**
MICROBOONE-NOTE-1108-PUB

Outline



The SBN Far Detector: ICARUS-T600

The ICARUS detector was the first large scale demonstration of LArTPC technology for neutrino physics, when it ran for 3 years (2010-2013) at Gran Sasso in Italy, using the CERN Neutrino to Gran Sasso (CNGS) beam.



It sits now at **600m** from the BNB target, as the **far-detector of the SBN program**, close to the oscillation maximum for O(1 eV^2) sterile neutrinos and has an **active volume over five times that of MicroBooNE!**

~Significantly increased exposure!

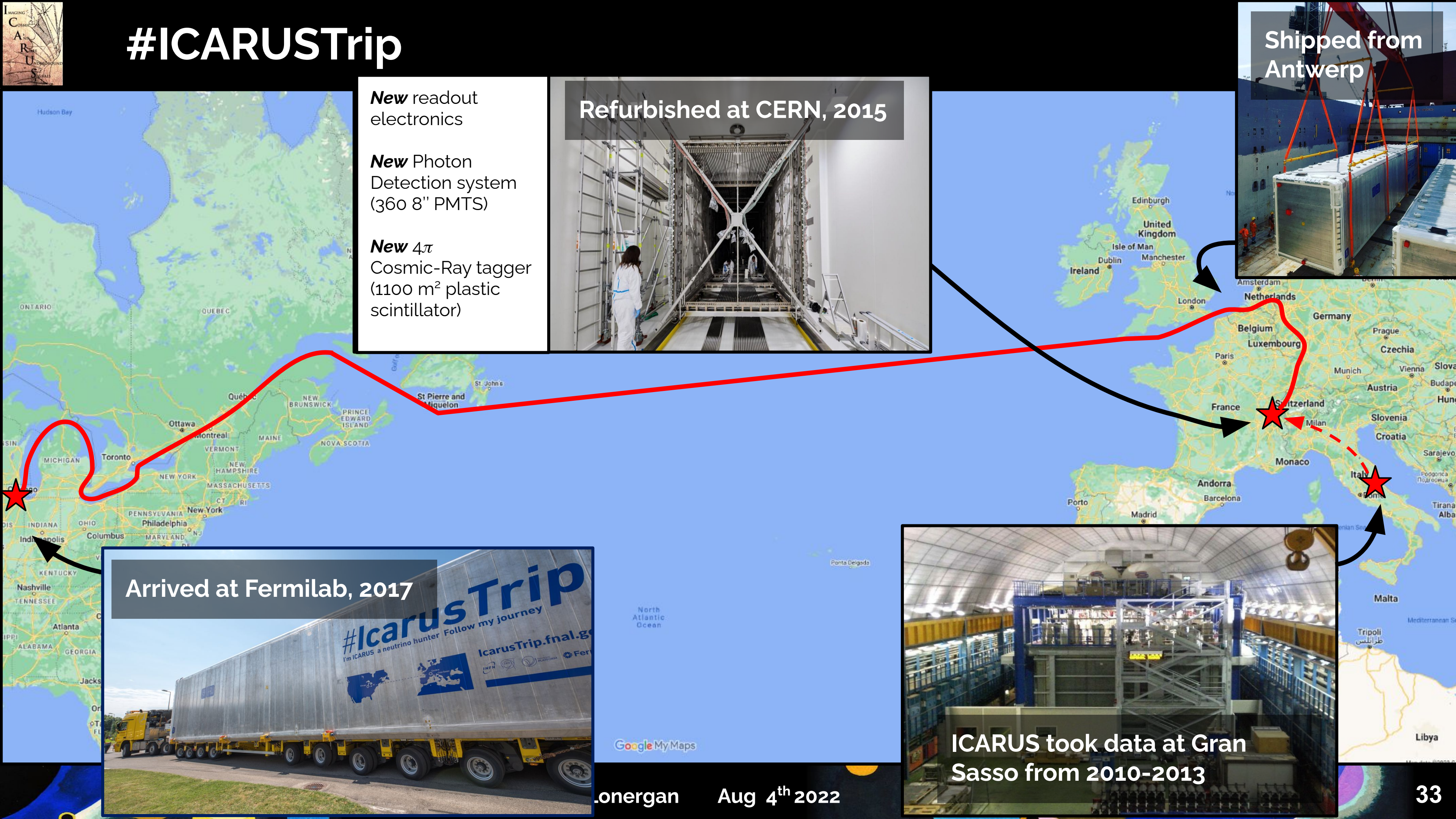
For more info see **Biswaranjan Behera's** talk [Aug 2nd, 4:18pm in WG1] on ICARUS's oscillation searches and **Minerba Betancourt's** talk [Aug 4th , 4:30pm in WG2,] on cross-section capabilities leveraging off-axis NuMI beam

#ICARUSTrip

New readout electronics

New Photon Detection system (360 8'' PMTS)

New 4π Cosmic-Ray tagger (1100 m² plastic scintillator)



Refurbished at CERN, 2015

Shipped from Antwerp

Arrived at Fermilab, 2017

ICARUS took data at Gran Sasso from 2010-2013

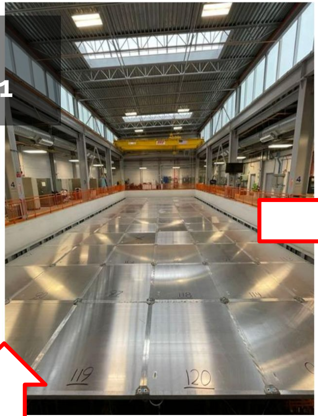
ICARUS's Timeline

Refurbished at CERN and moved to Fermilab in 2017!

Installation of cold vessel Aug 2018

Start of TPC/PMT operation, Aug 2020

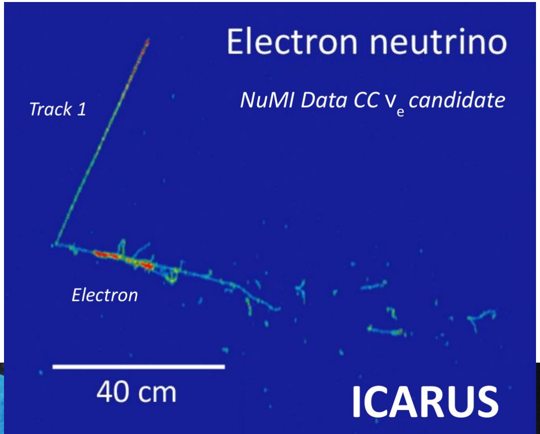
4π CRT installation complete, Dec 2021



For more info on ICARUS's cosmic rejection see **Biswaranjan Behera's** talk [Aug 5th, 4:39pm in WG5]

~3m concrete overburden installed, June 2022

Full physics data taking with BNB and NuMI began 9th June 2022!

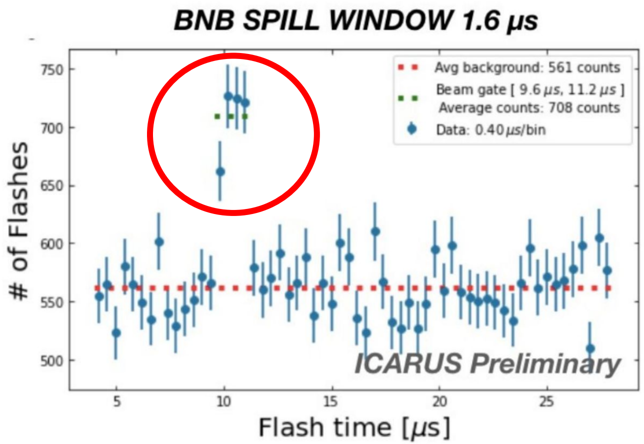


Commissioning the ICARUS detector at Fermilab

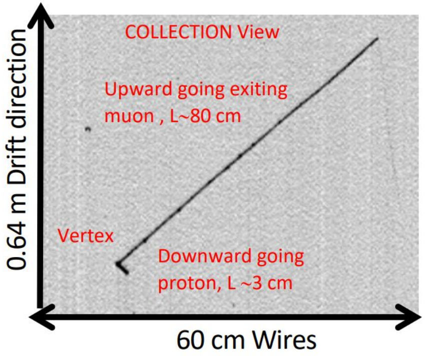
While physics data with full CRT and overburden began June 2022, **ICARUS was taking data with both BNB & NuMI beams since March 2021**, in parallel with commissioning activities.

This data that has been collected is being used for **trigger**, **calibration** and **reconstruction studies** that are in progress

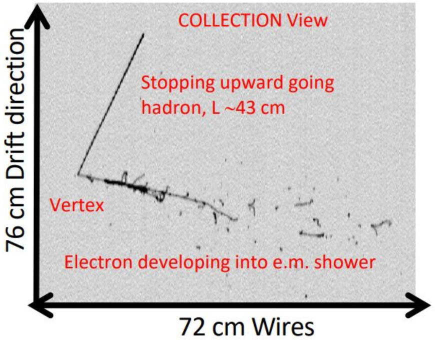
Excellent performance so far, the detector shows stable noise level with **electron lifetime > 3ms**



BNB CC QE muon neutrino candidate, E_{DEP} ~ 200 MeV

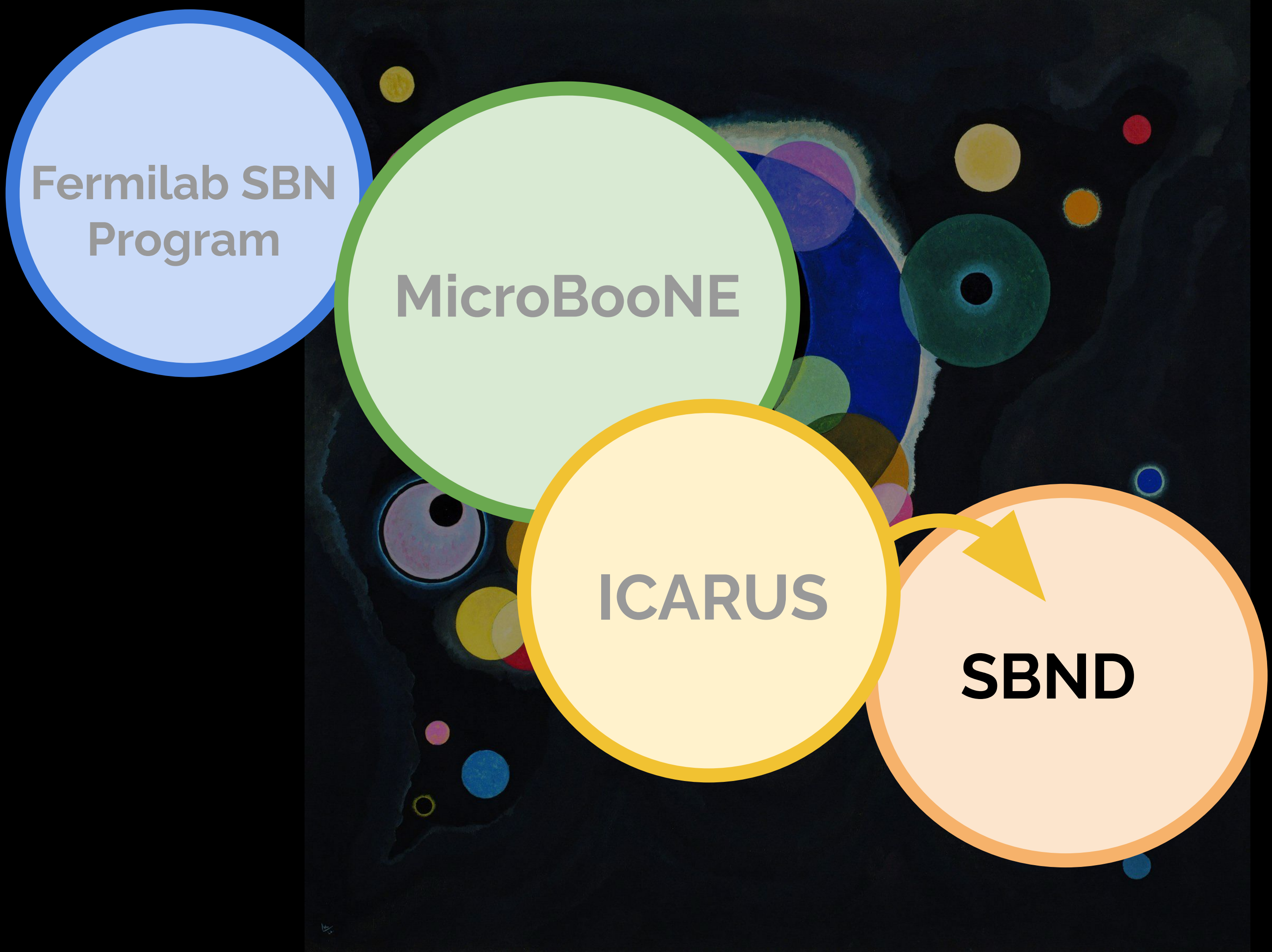


Contained NuMI CC QE electron neutrino candidate, E_{DEP} ~ 800 MeV



For more info on calibrations see **Gray Putnam's** talk Aug 5th, 3:32pm in WG6

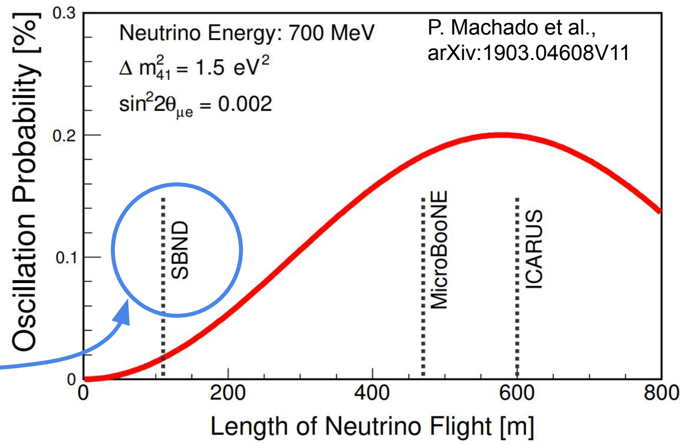
Outline



The Short-Baseline Near Detector (SBND)

SBND is a **brand new LArTPC** being constructed at Fermilab.

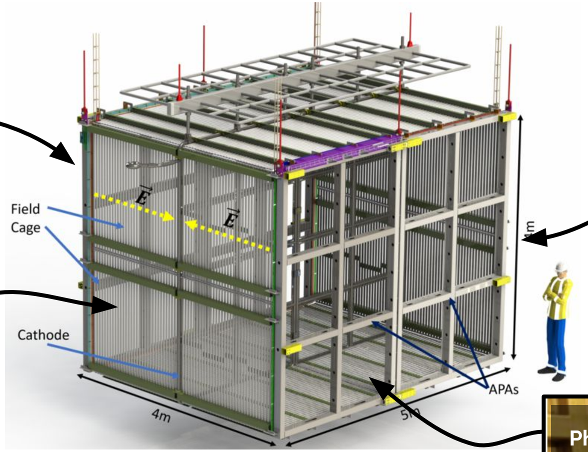
Located only **110m** from the BNB target, one of the main goals of SBND is to **constrain the un-oscillated flux** for sterile neutrino searches

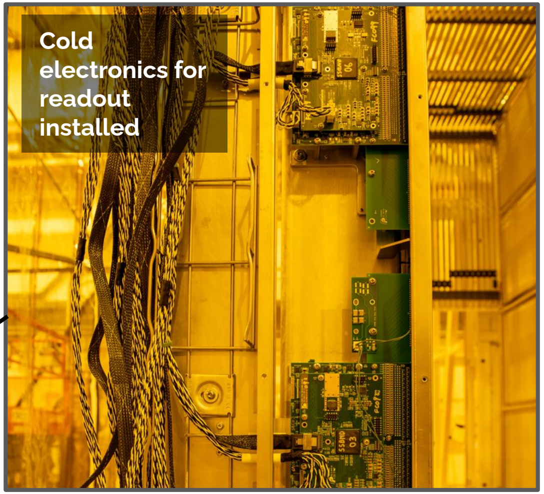


Given its proximity to neutrino production, the sheer number of neutrino-Argon interactions expected gives SBND unprecedented capability for improving our cross-section measurements

- More than **2 million neutrino interactions** will be collected per year
  - Of which **12,000 intrinsic ν_e interactions** will be recorded
- SBND will collects more data in 1 month, than MicroBooNE did in 2 years!

TPC Construction

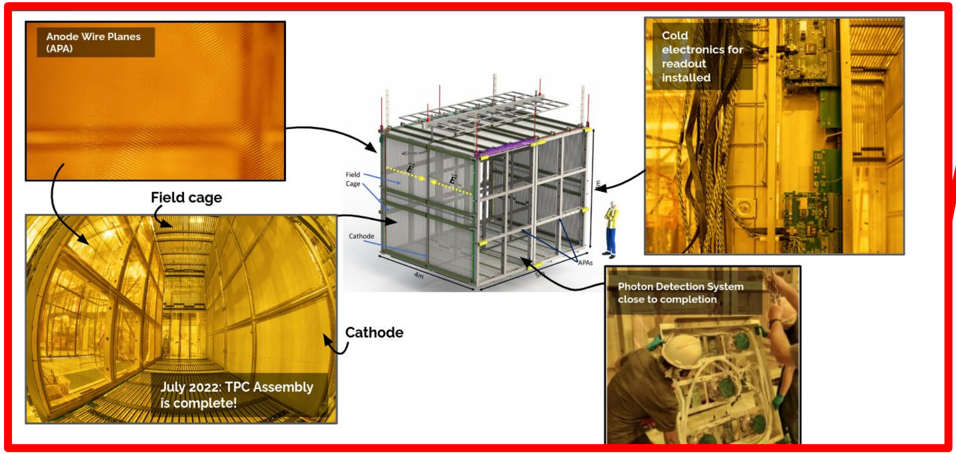


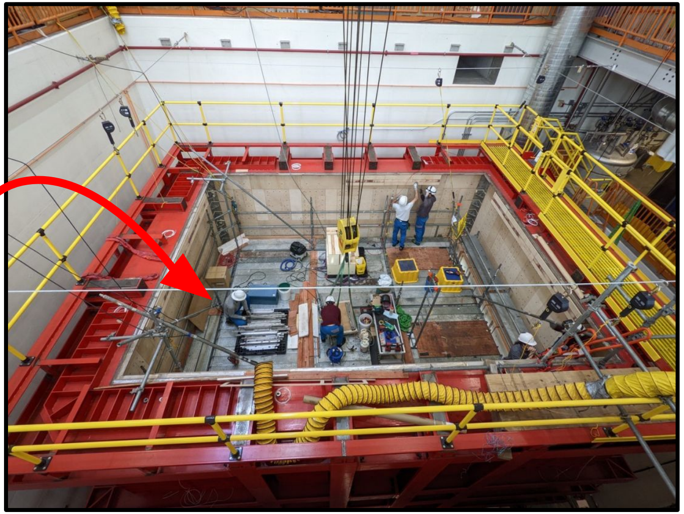


Field cage

Cathode

SBND Membrane Cryostat





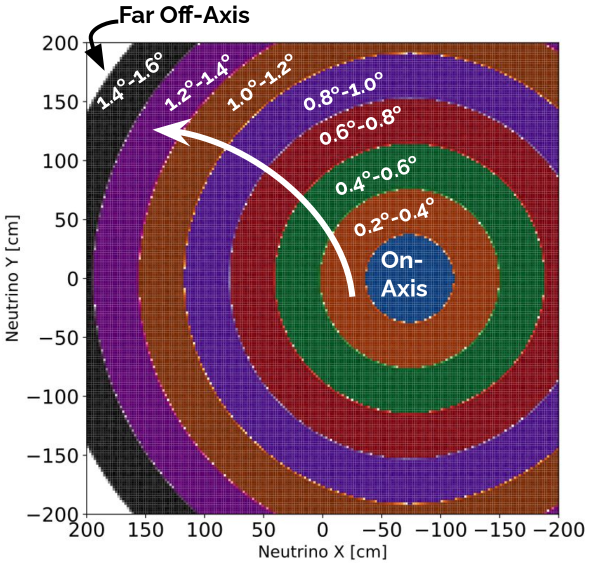
All this will sit inside a membrane cryostat.
Installation going well, 2 out 3 phases completed

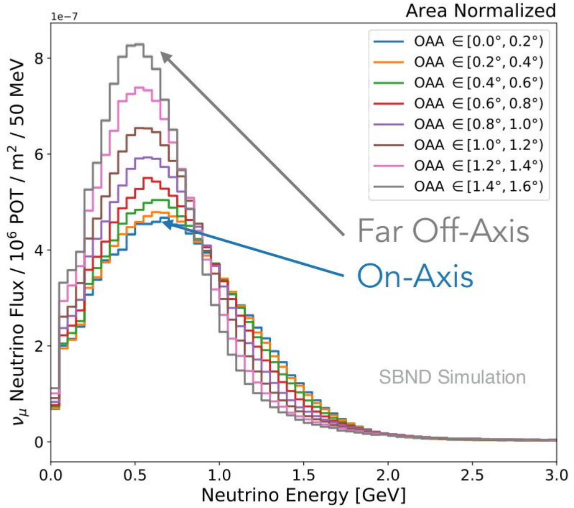
On track for filling & operation in late 2023

For complete info on SBND status and capabilities see **Miquel Nebot-Guinot's** talk Aug 2nd, 4.00pm in WG1 and **Gabriela Vitti Stenico's** talk on SBND trigger development Aug 4th, 4:50pm in WG6

SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector

As SBND is so close (~110m) to the intense BNB beam, different sections of the detector see different fluxes based on their effective off-axis angle.





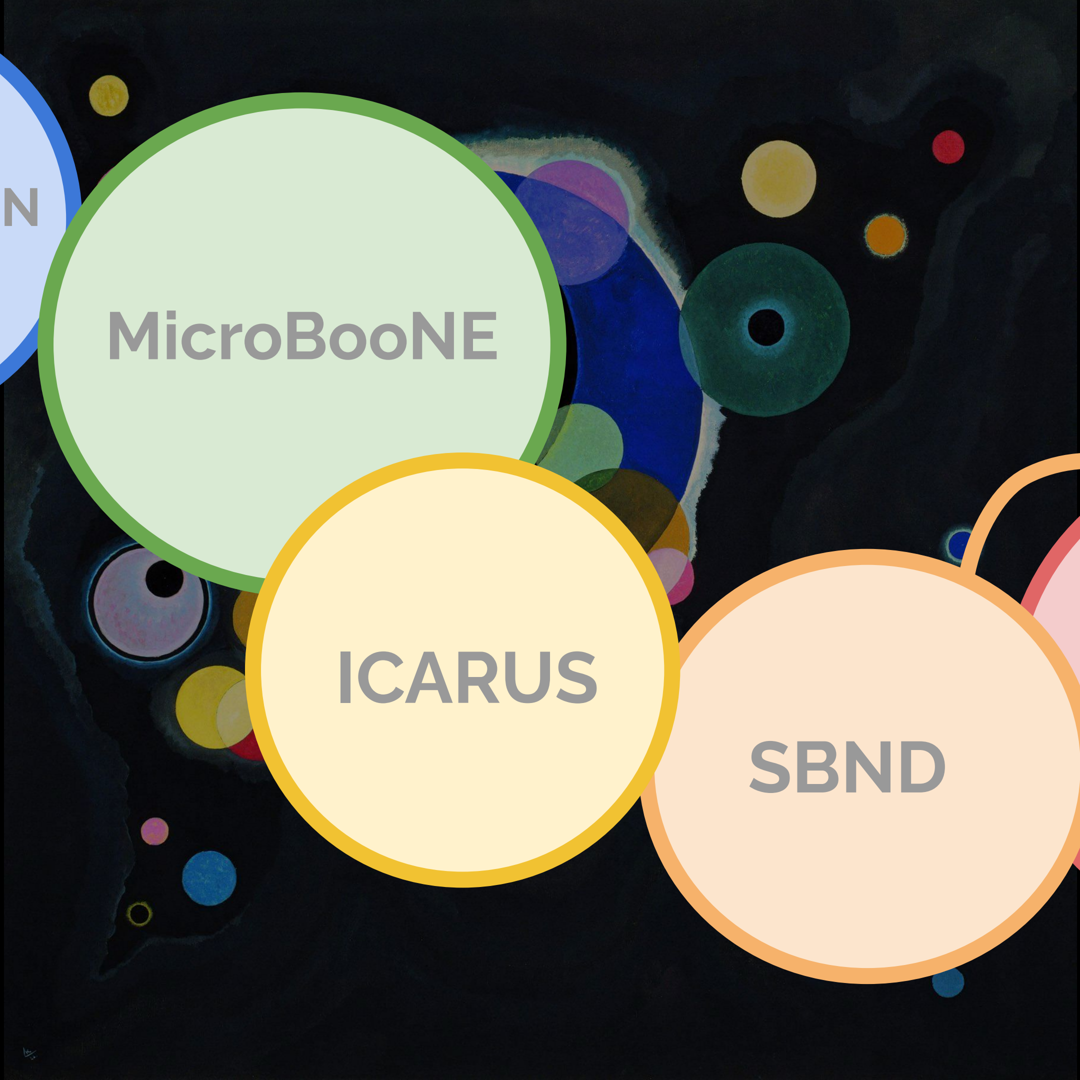
Ongoing studies exploring the physics potential of SBND-PRISM:

- Improve flux & cross-section constraints
- Study Energy Dependance of Cross Section
- Reduced backgrounds for increasing off-axis in BSM searches
- . . . and more!

Can select **lower energy**, more **mono-chromatic** beams by **going more off axis**.

For more info see **Marco Del Tutto's** talk [Aug 4th, 11:38am in WG1]

Outline



Fermilab SBN Program

MicroBooNE

ICARUS

SBND

Putting it all together: Full Sensitivities

ICARUS-T600 Factsheet

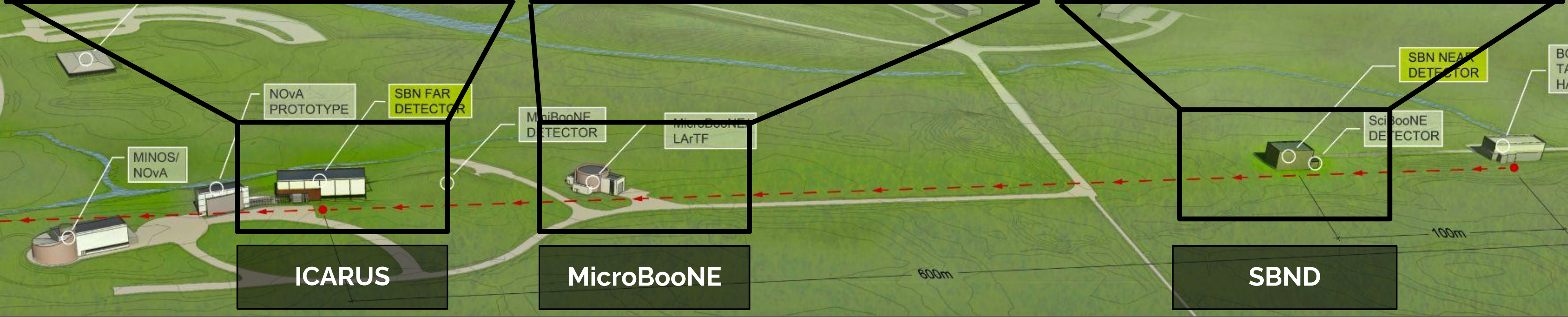
BNB Baseline: **600m**
Dimensions: 2x (19.6 x 3.6 x 3.9 m^3)
Total LAr mass 760 ton
Active LAr mass **476 ton**
-75 kV high voltage
1.5 m drift distance
53,248 Wires in TPC
360 8" PMTs

MicroBooNE Factsheet

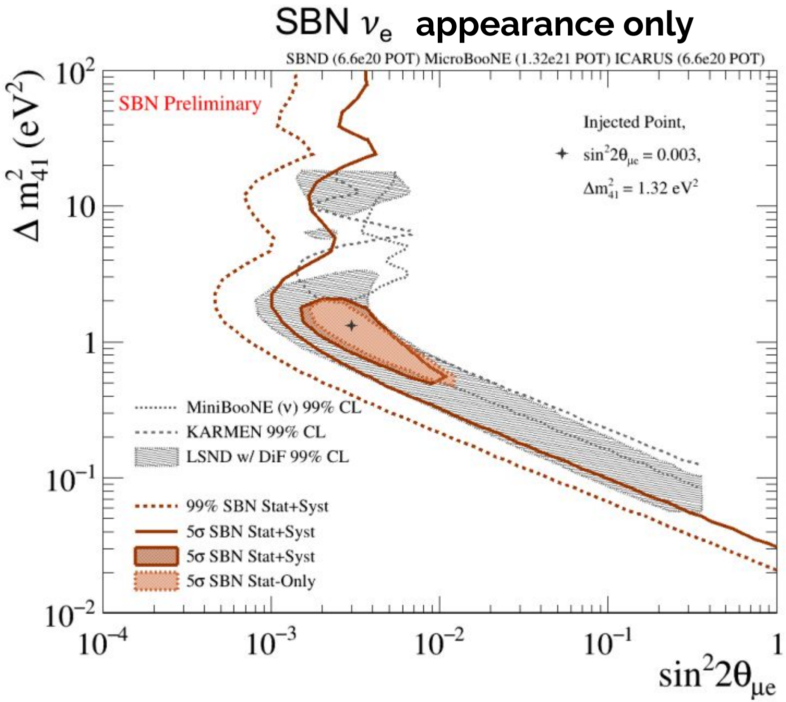
BNB Baseline: **470m**
Dimensions: (2.33 x 2.56 x 10.37 m^3)
Total LAr mass 170 ton
Active LAr mass **90 ton**
-70kV high voltage
2.5 m drift distance
8,256 Wires in TPC
32 8" PMTs

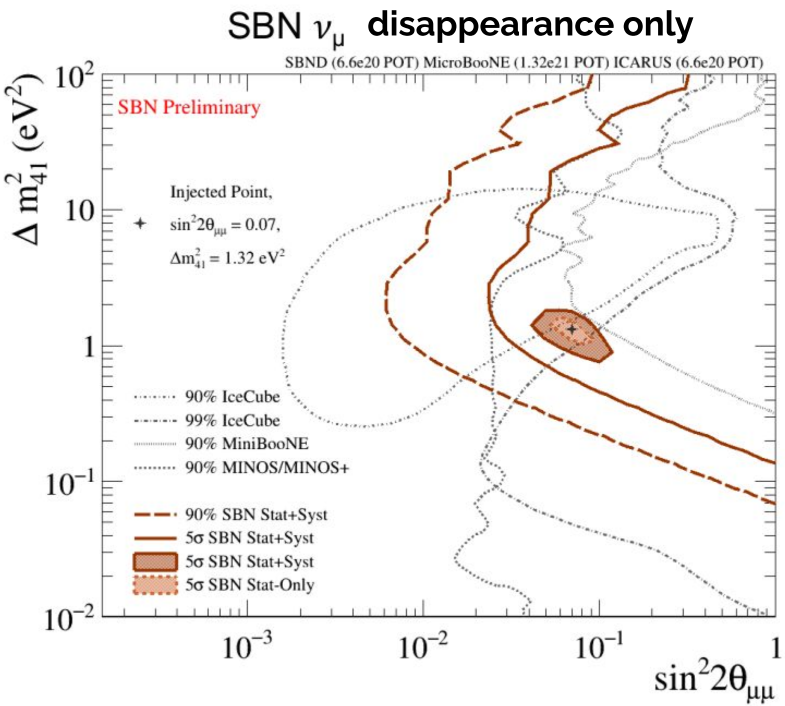
SBND Factsheet

BNB Baseline: **110m**
Dimensions: (4 x 4 x 5 m^3)
Total LAr mass 270 ton
Active LAr mass **112 ton**
-100 kV high voltage
2m drift distance
11,263 Wires in TPC
120 8" PMTs & 192 X-ARAPUCAs



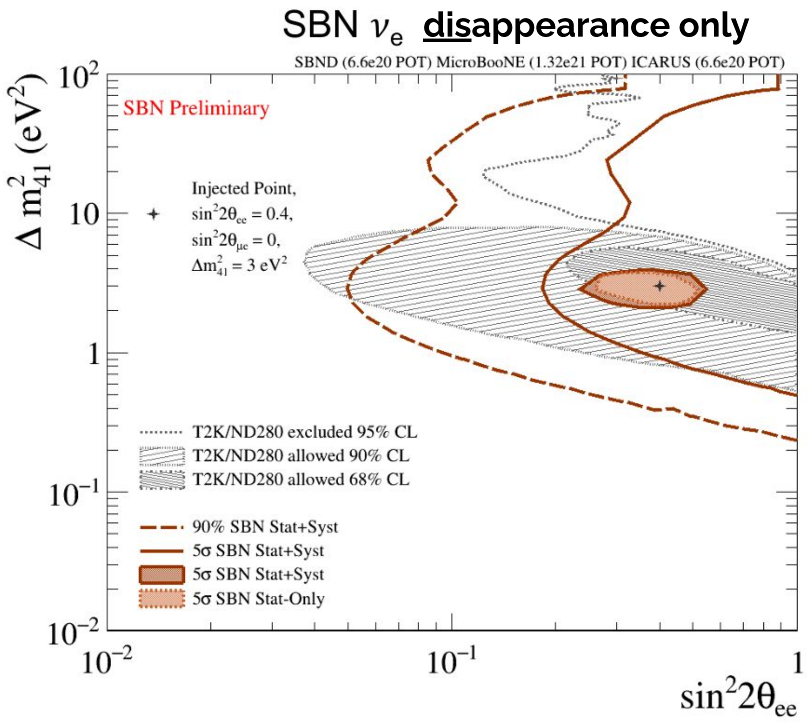
Sterile Neutrino Sensitivities





- SBN sensitivities for 6.6 x 10^{20} protons on the BNB target (MicroBooNE at 13.2e20) as per SBN proposal
- Updated from proposal sensitivities to reflect as-built detector size/position, more realistic systematics, etc..

Sterile Neutrino Sensitivities



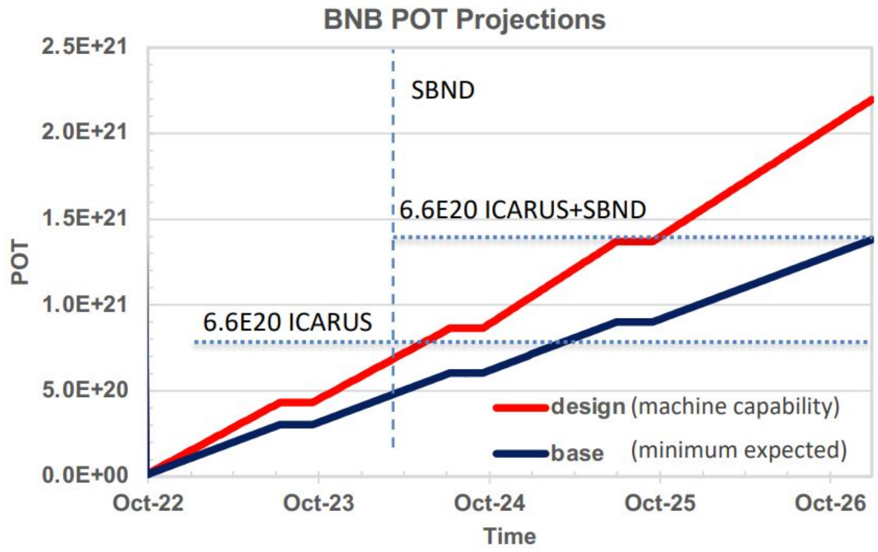
- As mentioned SBND will see over **35,000 intrinsic ν_e** in 6.6e20 POT.
- Allows for a direct accelerator based ν_e disappearance search, **complementary to both reactor and radioactive source ν_e disappearance experiments**
- In addition **ICARUS** will leverage its position ~5.7^o off axis in the **NuMI beam** to **perform a ν_e disappearance** search as part of **Neutrino-4 signal investigation**

Protons-on-target (POT) exposure

The BNB has delivered high quality beam for almost two decades, regularly achieving "design" capability

The original SBN proposal was for **6.6e20** POT

However, current plans are for BNB to continue to operate at design until the LBNF long-shutdown ~Jan. 2027.



As such by 2027

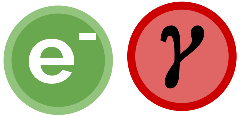
- **ICARUS** will have obtained over **x3 the proposal POT**
- **SBND+ICARUS** will have obtained over **x2 the proposal POT**
    - Stay tuned for updated sensitivities including larger dataset soon!

… and Beyond Simple 3+1 Sterile Neutrinos!

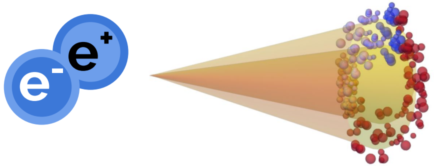
As a community, interest has expanded past simple 3+1 sterile neutrinos, and have opened up a whole new field where neutrinos might be the portal to a **"dark sector"** with rich and complex new interactions.

Rich phenomenology developing in recent years around the possibility of the MiniBooNE and LSND excess being due to **e^+e^- pairs from decays of new exotic particles** such as **dark-photons, axion-like particles or new scalars!**

Electrons or Photons?



or Overlapping e^+e^-



- Published results in MicroBooNE on decays of **Heavy Neutral leptons** and **Higgs Portal Scalars** (arXiv.2207.03840)
- Multiple ongoing analyses searching for **exotic e^+e^- production** due to **Dark neutrinos** in MicroBooNE as potential LEE explanation
- Developing **Boosted light dark matter** and **Millicharged particles** searches to take advantage of SBND's intense flux

For more info on SBND's BSM program see **Supraja Balasubramanian's** talk Aug 2nd, 4:36pm, WG5

Evolving Theory Landscape, not just a simple sterile ν anymore!

- **Decay of O(keV) Sterile Neutrinos** to active neutrinos
  - *Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New **resonance matter** effects
  - *Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
  - *Alves, Louis, deNiverville, [hep-ph]2201.00876 (2022)*
- **Mixed** O(1eV) sterile **oscillations and** O(100 MeV) **sterile decay**
  - *Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of **heavy sterile neutrinos produced in beam**
  - *Gninenko, Phys.Rev.D83:015015,2011*
  - *Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
  - *Dutta, Kim, Thompson, Thornton, Van de Water [hep-ph]2110.11944*
- Decay of **upscattered heavy sterile neutrinos** or new scalars mediated by **Z'** or more **complex higgs sectors**
  - *Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)*
- Decay of **axion-like particles**
  - *Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*

Produces True Electrons

Produces True Photons

Produces e^+e^- pairs

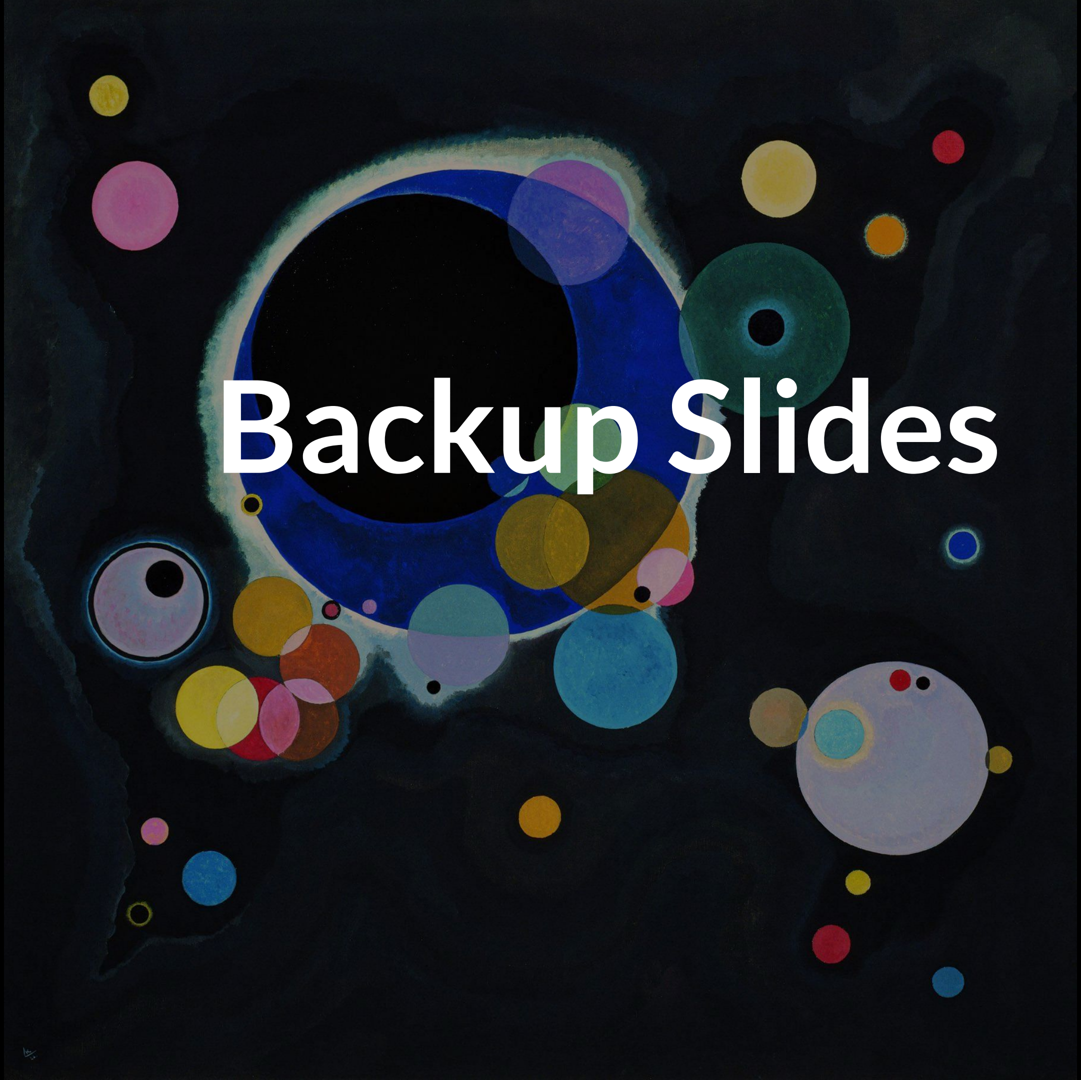
The SBN program is the perfect platform to explore to this *rapidly growing field*! Majority of these in last couple years!

(Caution: not an exhaustive list!)

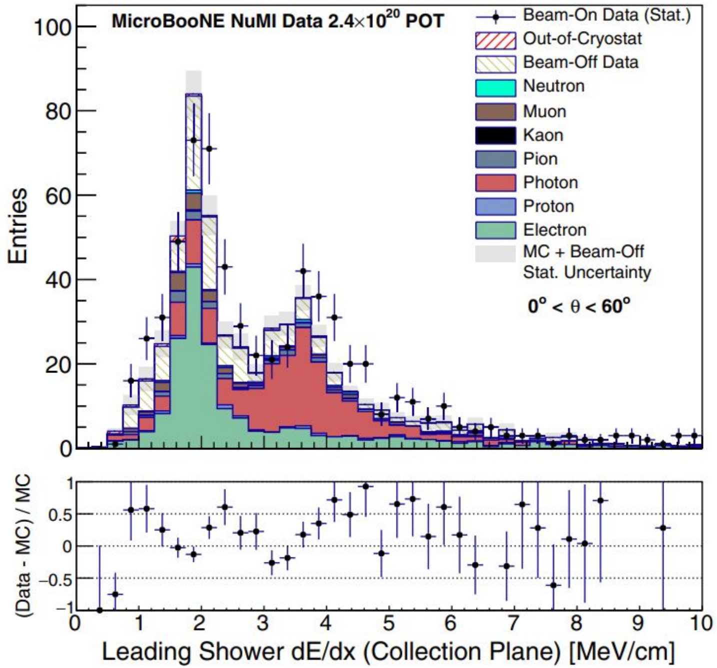
- **MicroBooNE** has finished its data collection.
    - First LEE results on ~½ data set released in 2021, with analyses utilizing the rest well on their way
- **ICARUS** operating very well in commissioning mode and has begun first physics run as of June 2022
    - ICARUS will reach nominal dataset by mid-2024
- **SBND** Installation is progressing very well, and is on track for operation in late 2023
- Expect **2-3X higher statistics** for SBND/ICARUS than proposal by 2027
- The **SBN program** is going to be a **BSM factory** capable of probing many of the exciting new models in the community!

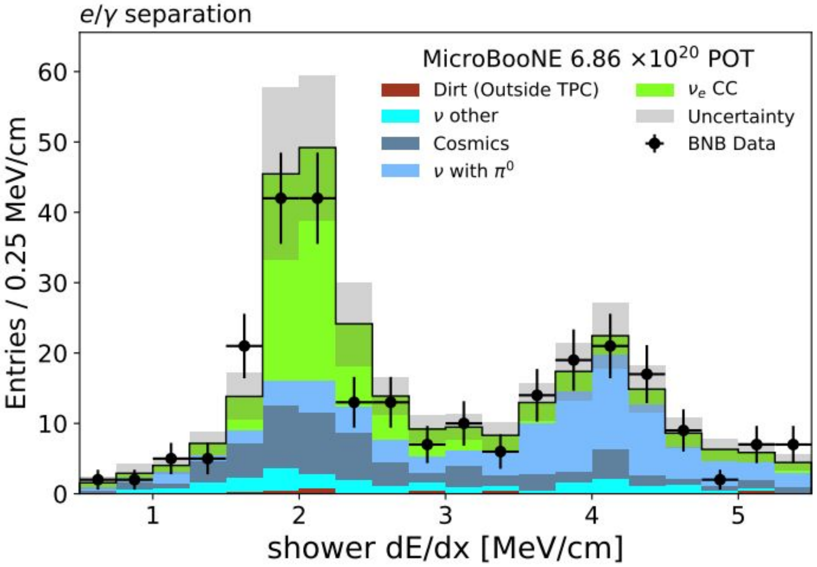


Backup Slides



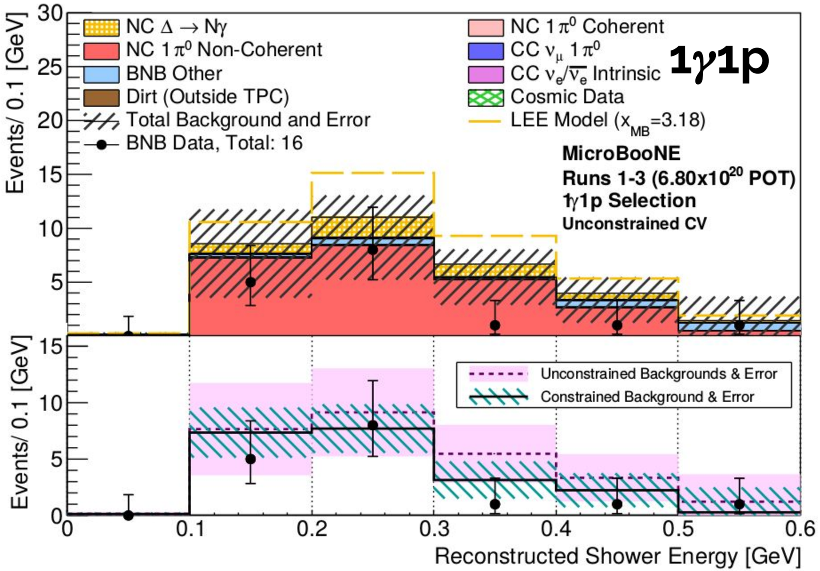
LArTPC electron-photon separation

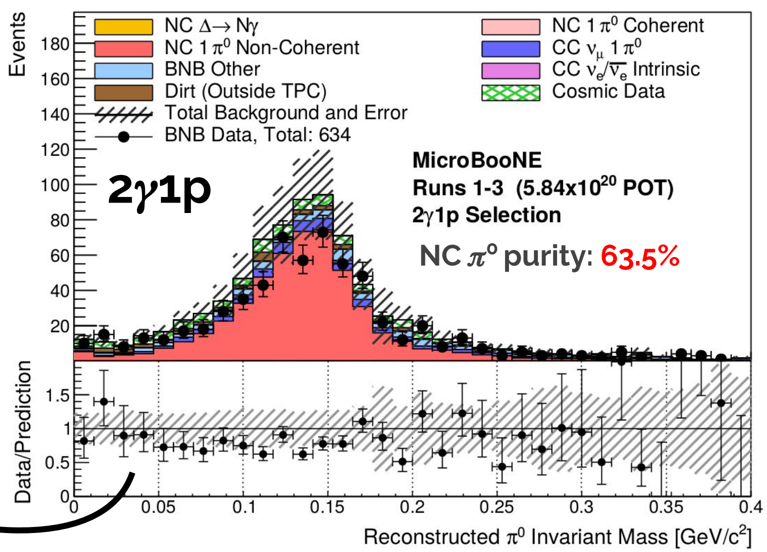




https://journals.aps.org/prd/pdf/10.1103/PhysRevD.104.052002

https://doi.org/10.1103/PhysRevD.105.112004

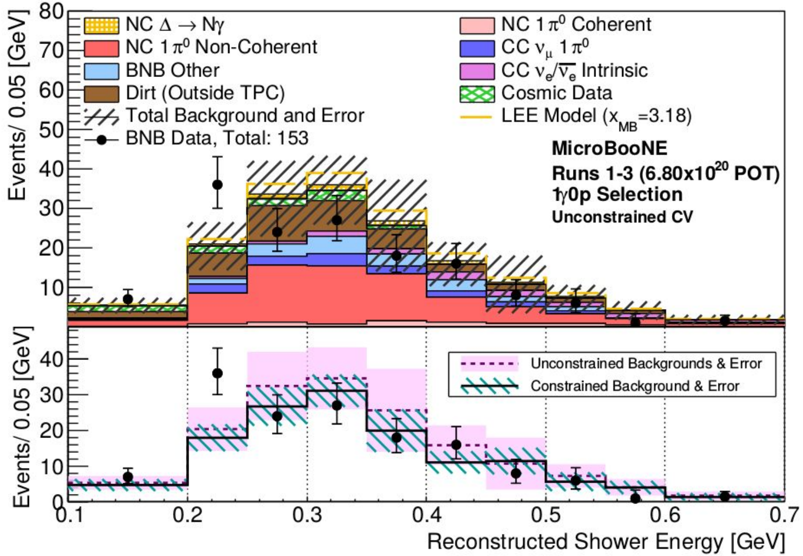




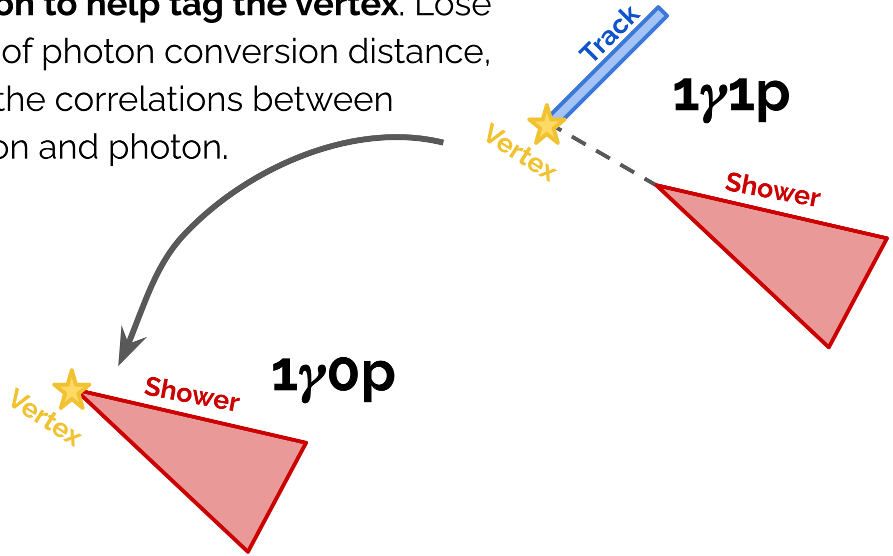
Use high statistics NC π^0 2γ1p sample to **constrain** the NC π^0 backgrounds in signal rich 1γ1p sample

Constraint has two effects:

- Overall **drop in expected backgrounds** by **24.1%**
- **Reduction in systematic uncertainty (29.8% →17.8%)**



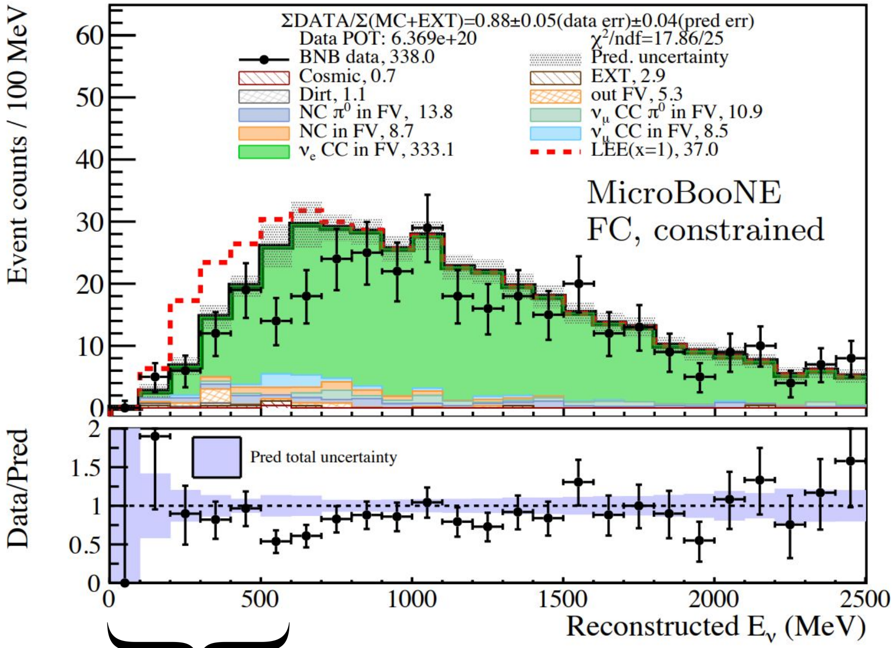
Going from 1γ1p to 1γ0p we lose the **proton to help tag the vertex**. Lose idea of photon conversion distance, and the correlations between proton and photon.



Overall, this results in a lower NC $\Delta \rightarrow N\gamma$ purity and a more **diverse category of backgrounds** (still NCπ^0 dominant).

Less sensitive to enhanced NC $\Delta \rightarrow N\gamma$ rates.

Quantify: How well does data agree with our constrained prediction?



p-value = 0.848

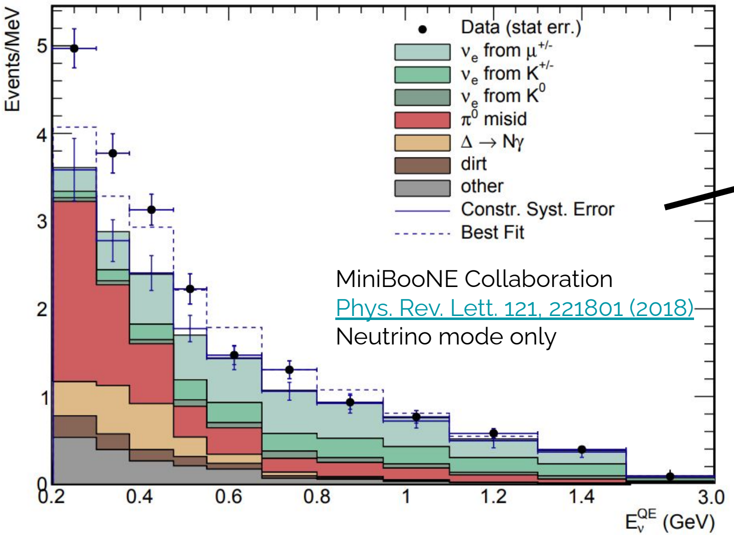
p-value = 0.448

From this we can conclude that the **observed data is in good agreement with our predicted ν_e**

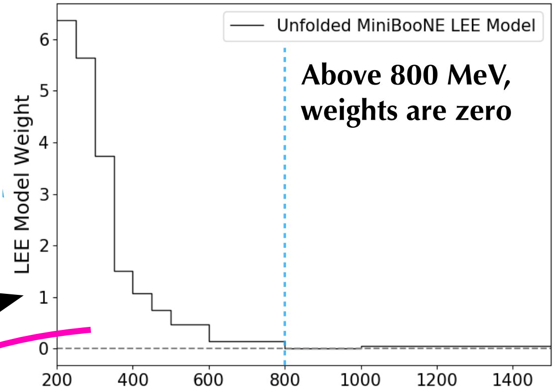
How much additional ν_e is needed to explain the anomaly?

Unlike **NC $\Delta \rightarrow N\gamma$** can't just use a flat scaling here as the **shape of intrinsic ν_e is completely different!**

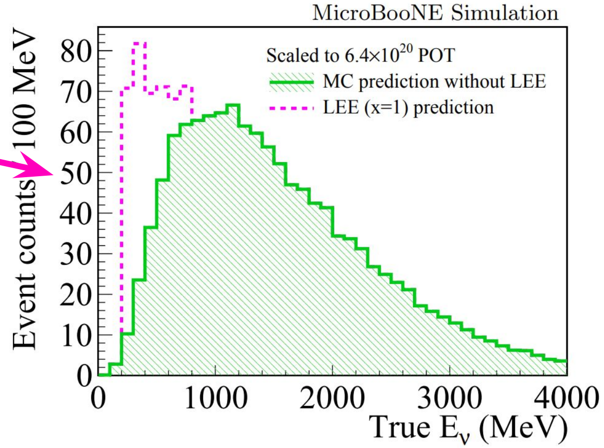
Need an **energy dependent scaling**



Unfold the MiniBooNE data under the hypothesis the excess is solely due to intrinsic ν_e



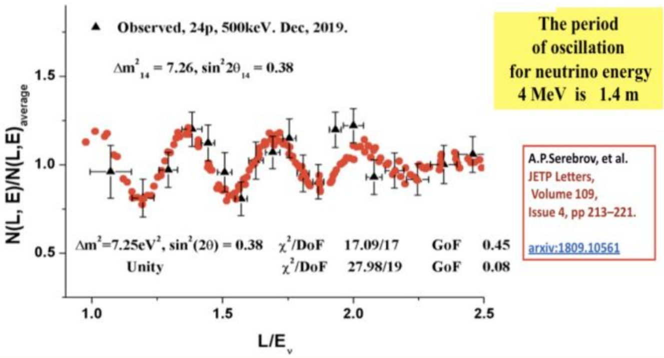
Map this to MicroBooNE by scaling our prediction of the ν_e spectrum!



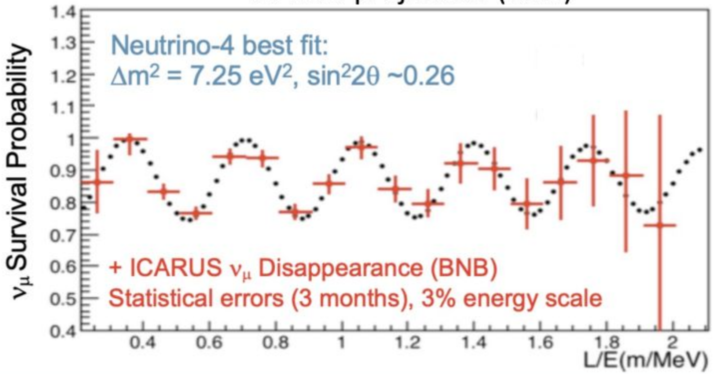
Search for Neutrino-4 Oscillation signal with ICARUS

- The Neutrino-4 collaboration claim a reactor neutrino disappearance signal with a clear modulation with L/E ~1-3 m/MeV
- ICARUS has sensitivity to this parameter space as a single-detector and is planning an oscillation analysis investigating the Neutrino-4 signal using data taken in the coming year (prior SBND operations)
- ICARUS will do analyses in two independent channels using different neutrino beams
  - ν_μ disappearance using the BNB
  - ν_e disappearance using NuMI

NEUTRINO-4 reactor signals



ICARUS projection (BNB)



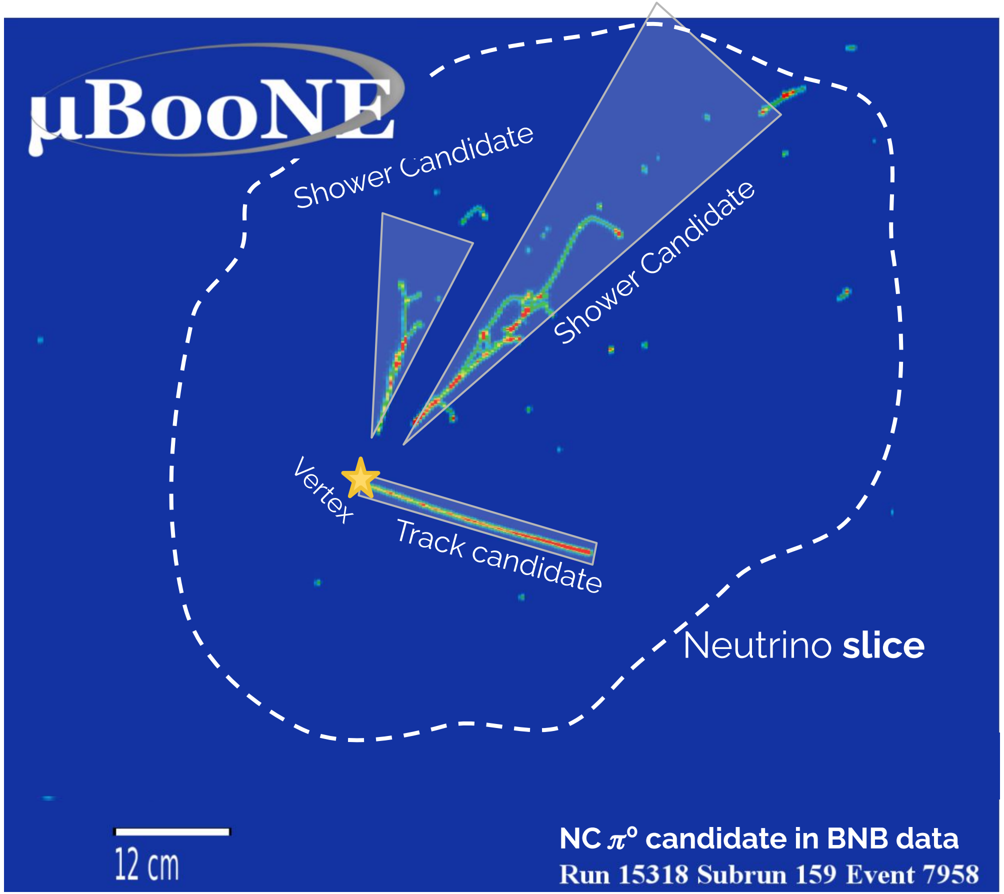
Pandora Reconstruction

Based on the pandora reconstruction framework as already mentioned in the Photon NC Δ radiative search.

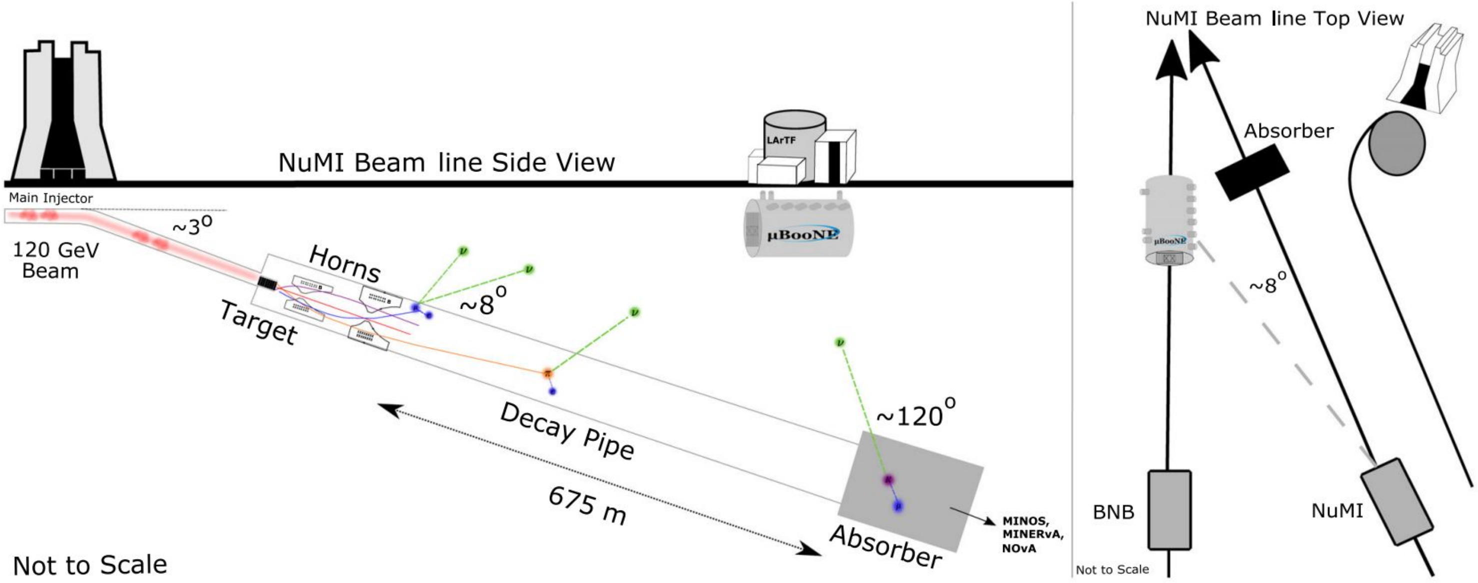
MicroBooNE has extensive experience with Pandora based reconstruction.

MicroBooNE publications using Pandora!

arxiv:2110.00409(2021)
arxiv:2109.06832 (2021)
arxiv:2109.02460(2021)
Phys. Rev. Lett. 127, 151803 (2021)
JINST 16 (2021) 09, P09025
Phys. Rev. D 104, 052002 (2021)
JINST 16 (2021) 04, P04004
Phys. Rev. D 102, 112013 (2020)
JINST 15 (2020) 12, P12037
Phys. Rev. Lett. 125, 201803 (2020)
Phys. Rev. D 101, 052001 (2020)
JINST 15 (2020) 02 , P02007
JINST 15, P03022 (2020)
Eur.Phys.J.C 79 (2019) 8, 673
Phys. Rev. D 99, 091102 (2019)
Eur. Phys. J. C (2019) 79:248
JINST (2017) 12 P12030



NuMi @ MicroBooNE



Search for Neutrino-4 Oscillation signal with ICARUS

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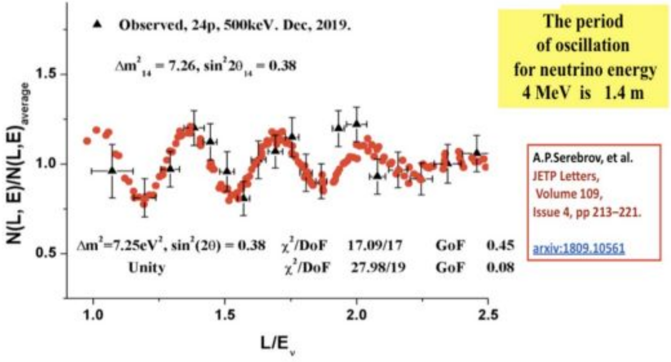
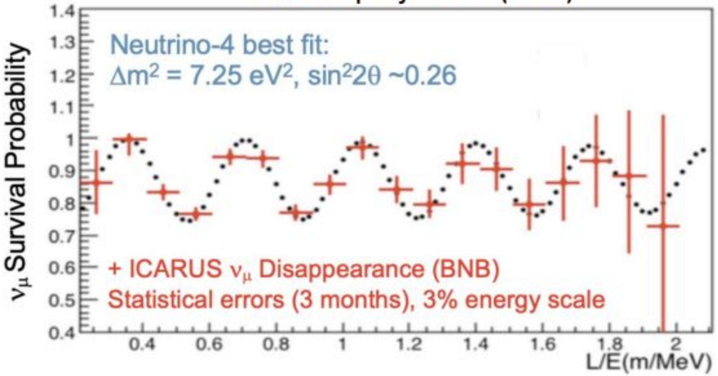
NEUTRINO-4 reactor signals



ICARUS projection (BNB)

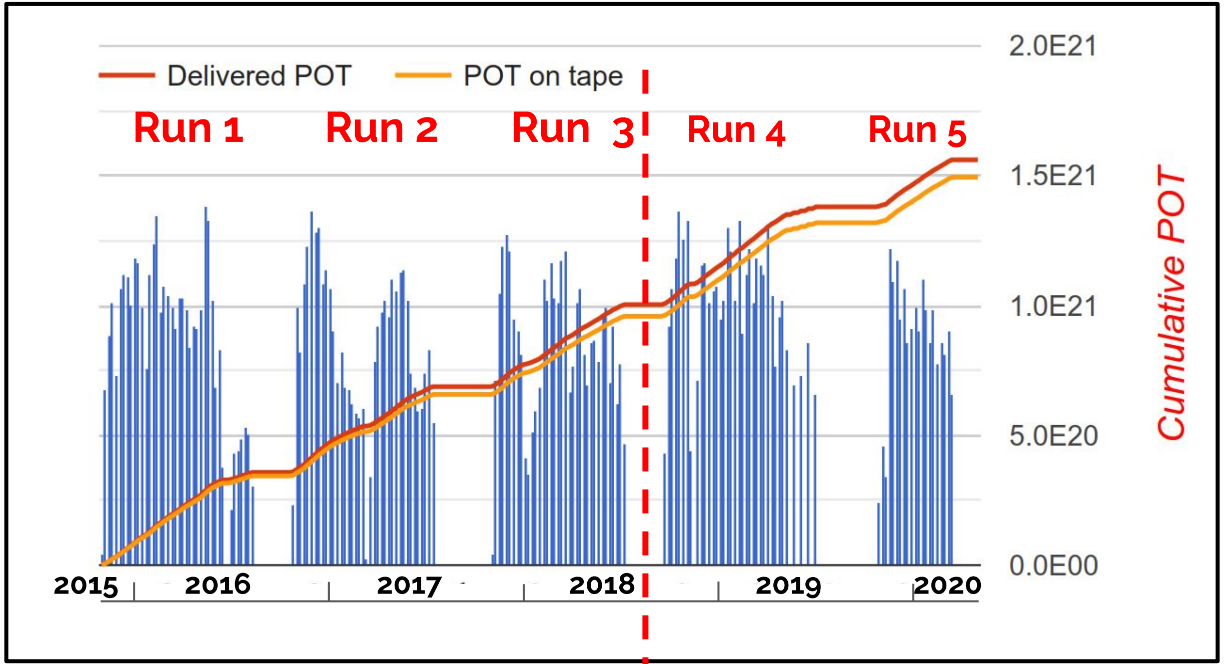


18 R.J.Wilson/CSU SBN@Fermilab

Slide From Bob Wilsons Snomass talk [LINK]

Successful running for over 5 years

Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**

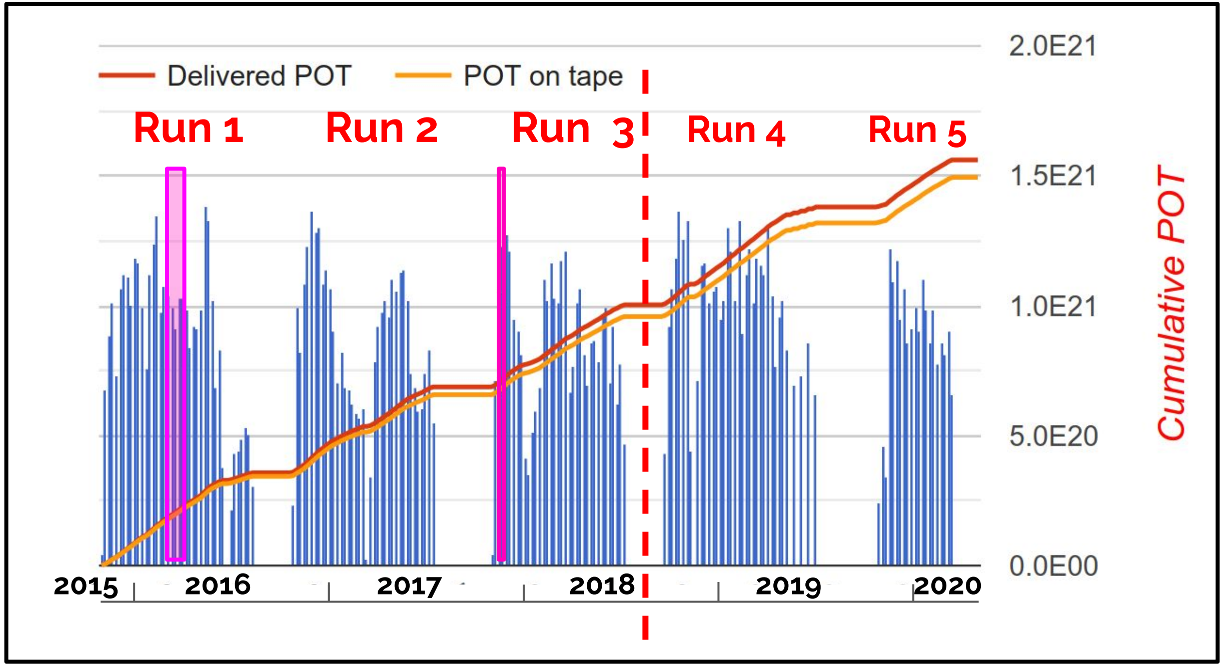


In today's talk I will be presenting results based on **6.80x10^{20} protons-on-target (POT)** from **Runs 1-3**

Analyzing remaining ½ of our data from Runs 4-5 is well underway!

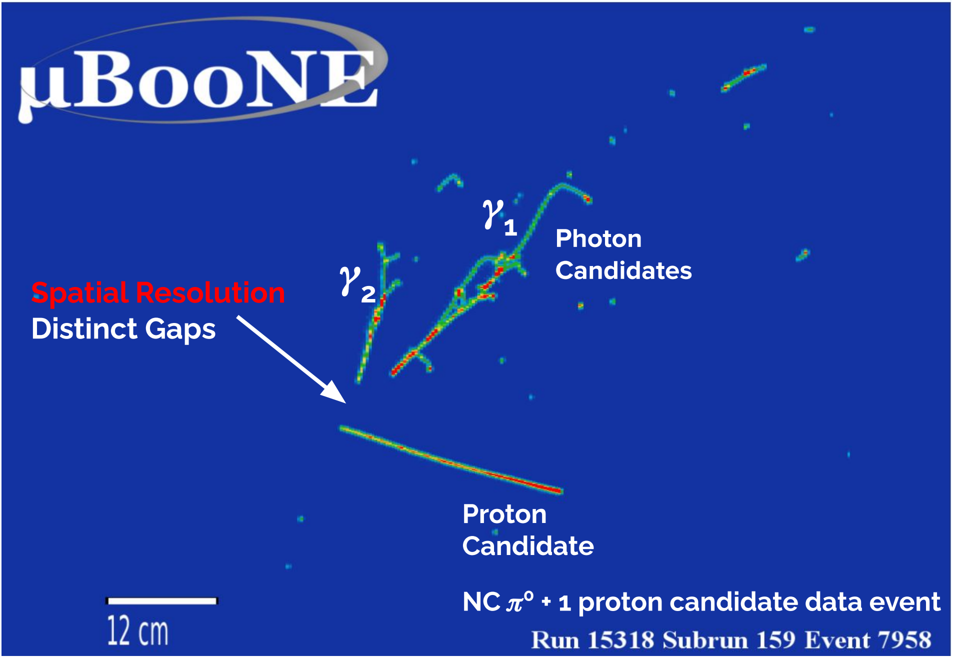
Successful running for over 5 years

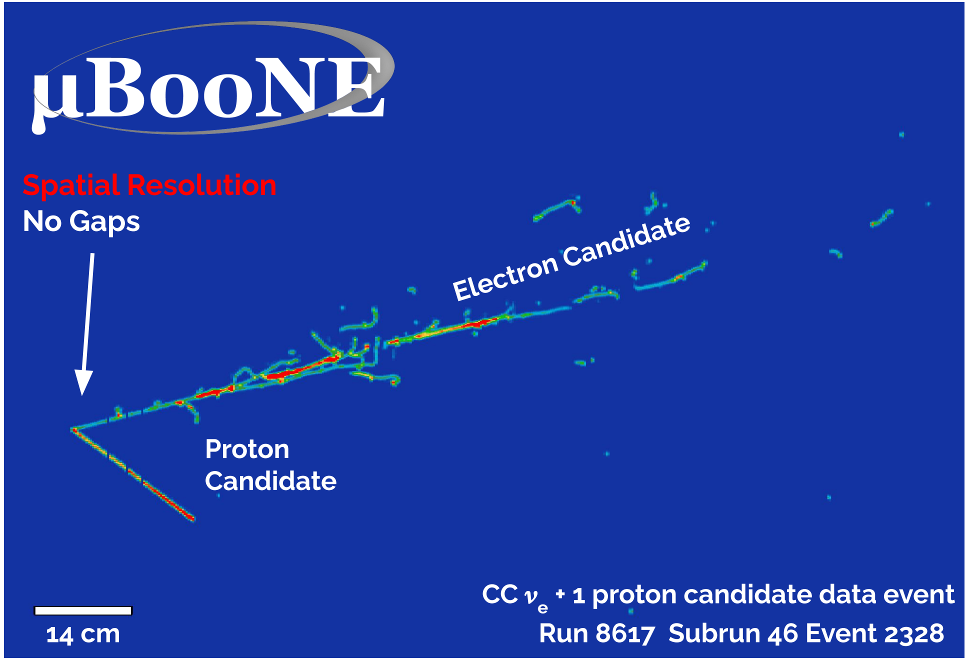
Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**



MicroBooNE uses **blind analyses,** so all **development** and **validation** took place first using a small unblinded **0.4×10^{20} POT** from Run 1 sample (~1/17th the size) and **0.1×10^{20} POT** from Run 3 sample

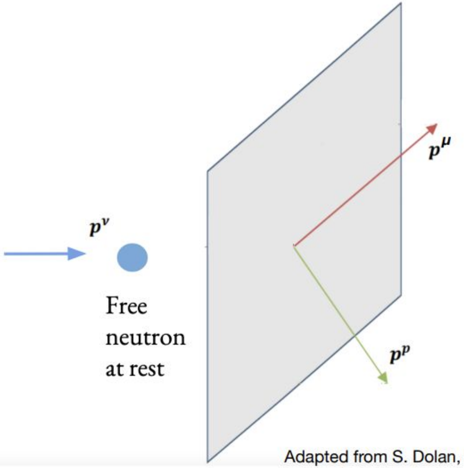
LArTPC's give us **fully active calorimeter** alongside **high-resolution tracking**





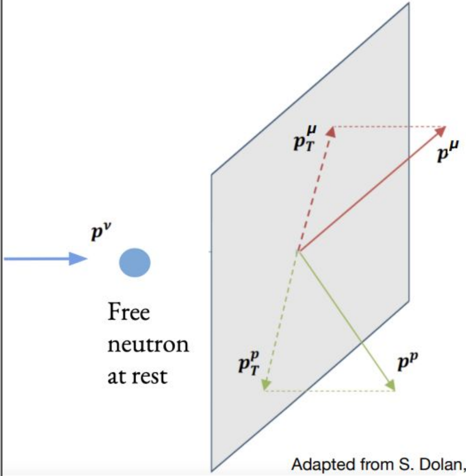
Allows for strong **photon** ↔ **electron separation**

Transverse kinematic imbalance (TKI)



Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]"

Transverse kinematic imbalance (TKI)

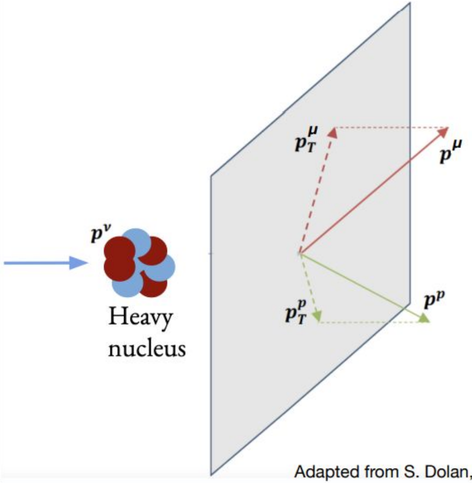


$$\delta p_T = \left| \mathbf{p}_T^\mu + \mathbf{p}_T^p \right| = 0$$

Transverse projections **trivially equal and opposite** (momentum conservation)

Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]"

Transverse kinematic imbalance (TKI)

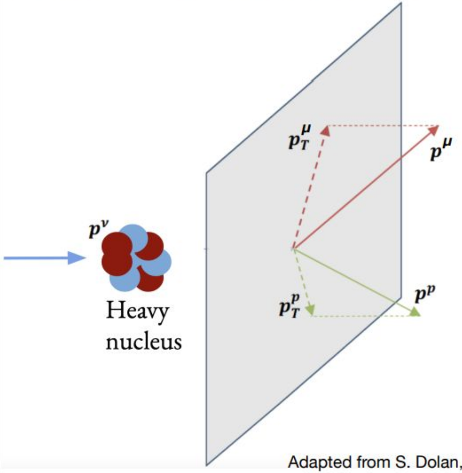


$$\delta p_T = \left| \mathbf{p}_T^\mu + \mathbf{p}_T^p \right| > 0$$

Imbalance due to initial nucleon motion and other nuclear effects

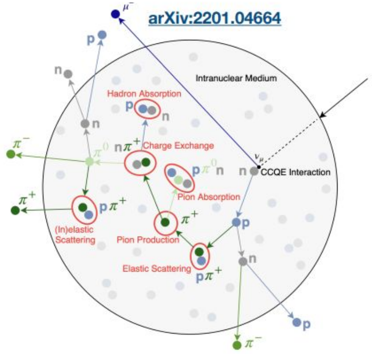
Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]"

Transverse kinematic imbalance (TKI)



Hadronic final-state interactions (FSI)

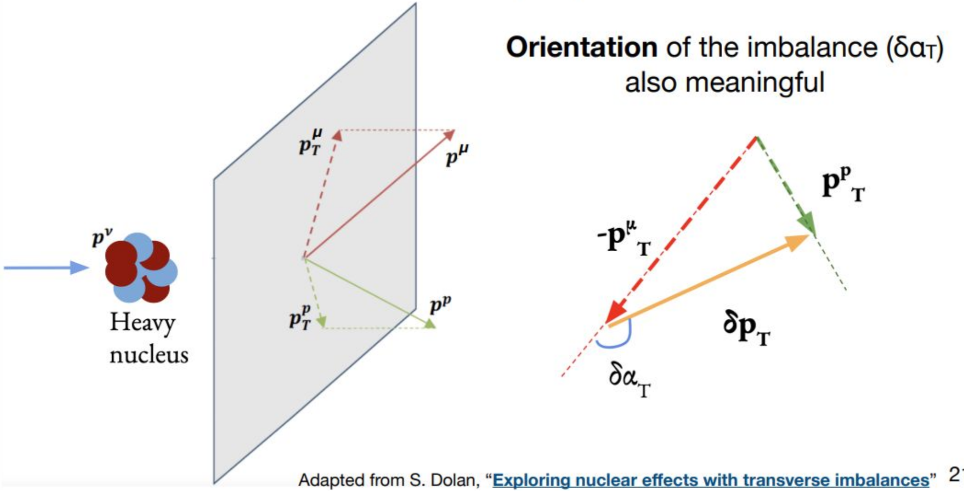
arXiv:2201.04664



Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]"

Transverse kinematic imbalance (TKI)

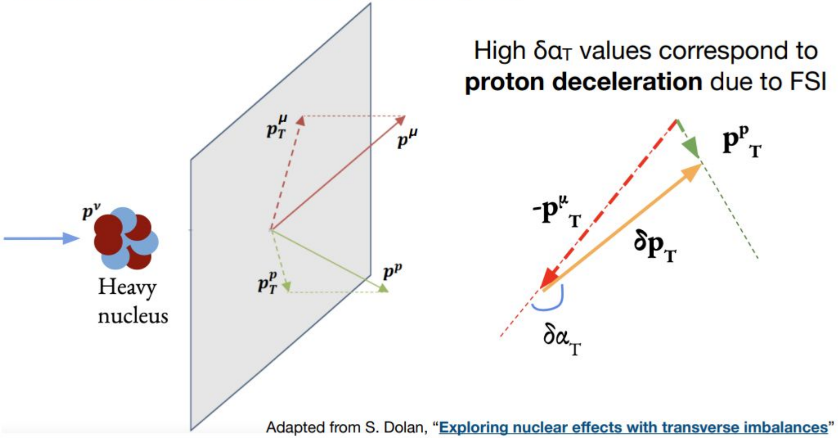
Orientation of the imbalance ($\delta\alpha_T$) also meaningful



Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]" 21

Transverse kinematic imbalance (TKI)

High $\delta\alpha_T$ values correspond to **proton deceleration** due to FSI



Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]" 22