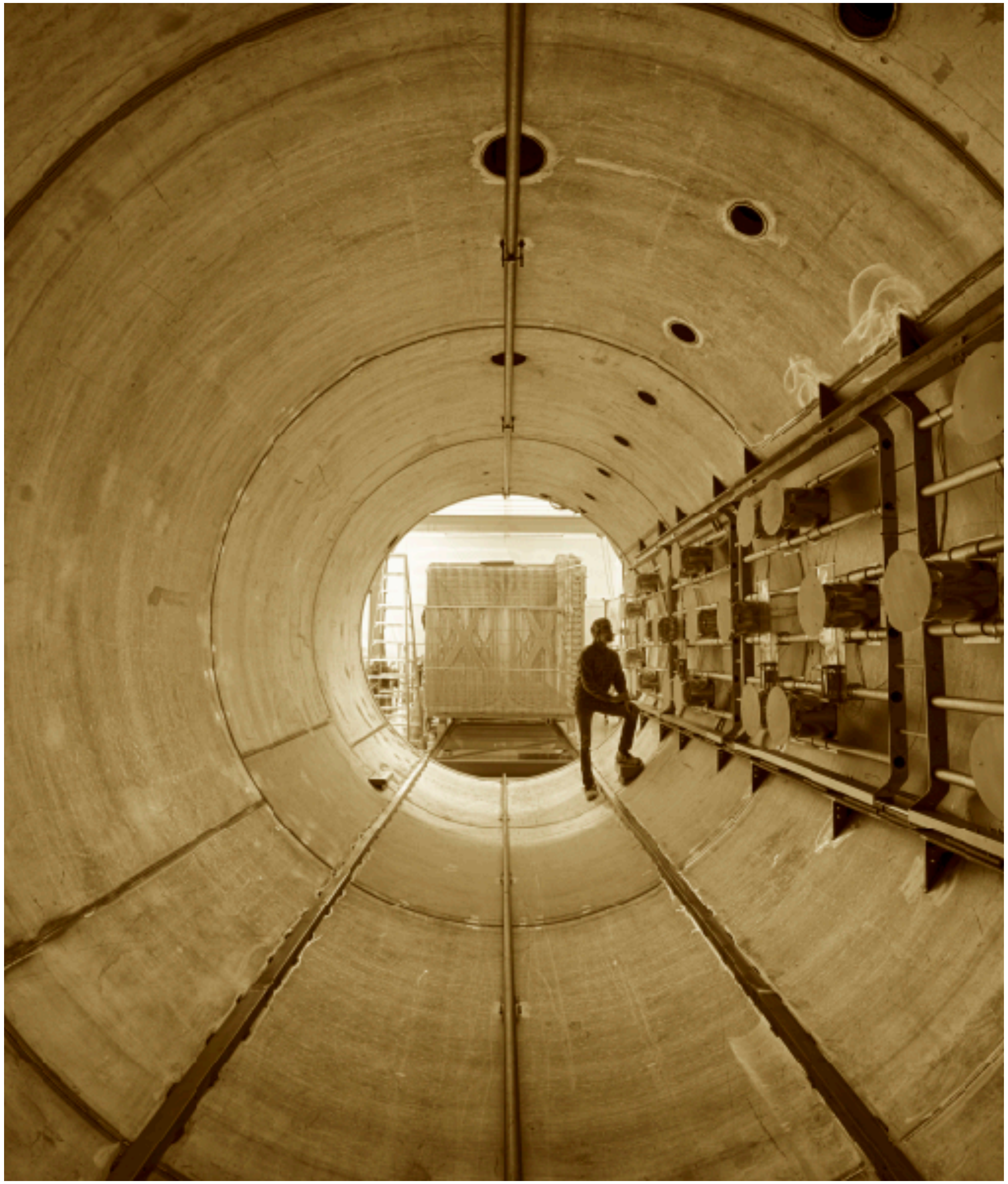
Latest results on sterile neutrino search and prospects with Fermilab SBN program

M. Nebot-Guinot for the MicrooBooNE Collaboration
Neutrino Workshop at IFIRSE
Jul 18, 2023

Outline

- Short-Baseline neutrino anomalies
- LArTPCs
- The MicroBooNE experiment
  - First results
  - Ongoing analysis
- The SBN Program



MicroBooNE cryostat with PDS on the right and TPC at the back ready to be installed

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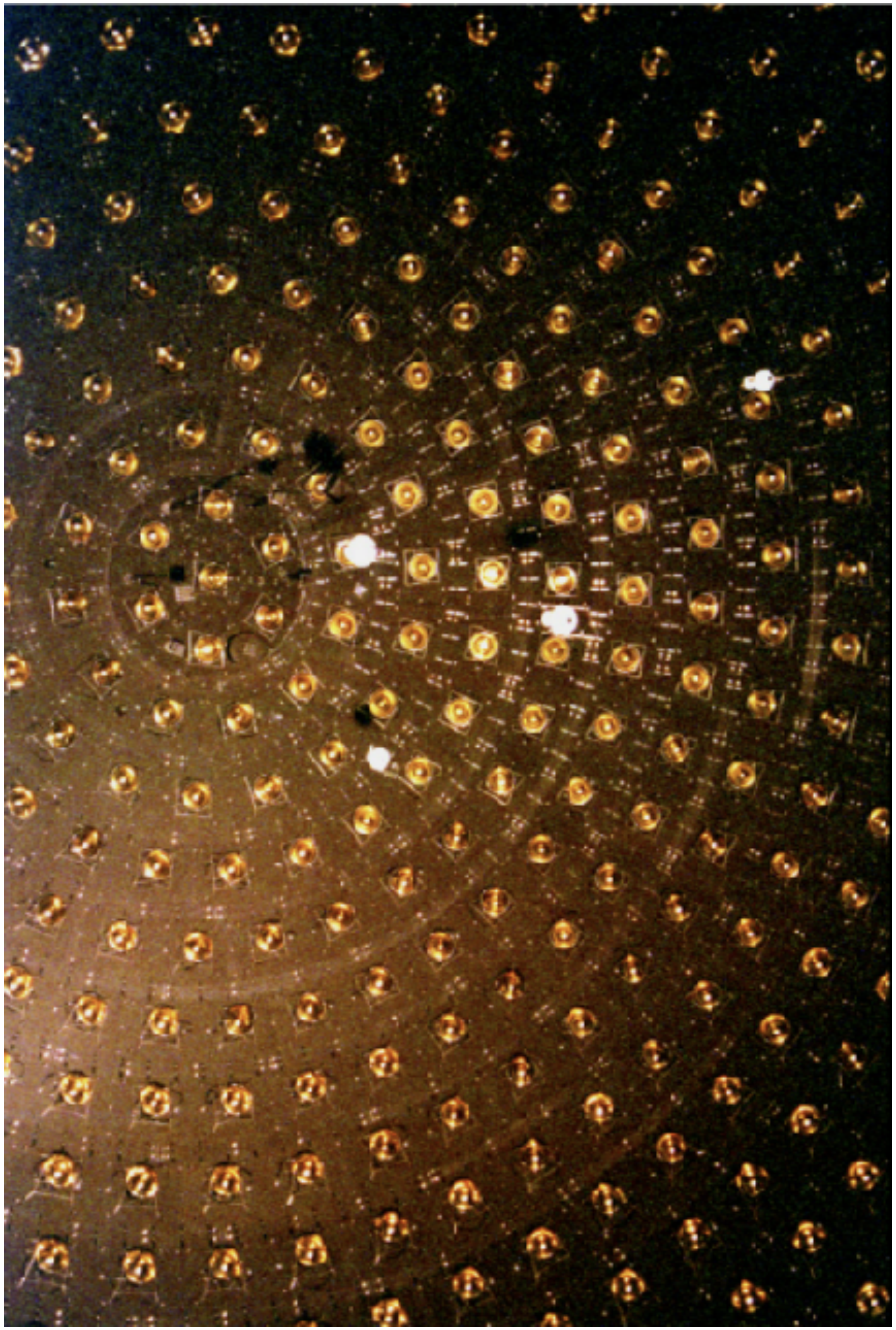


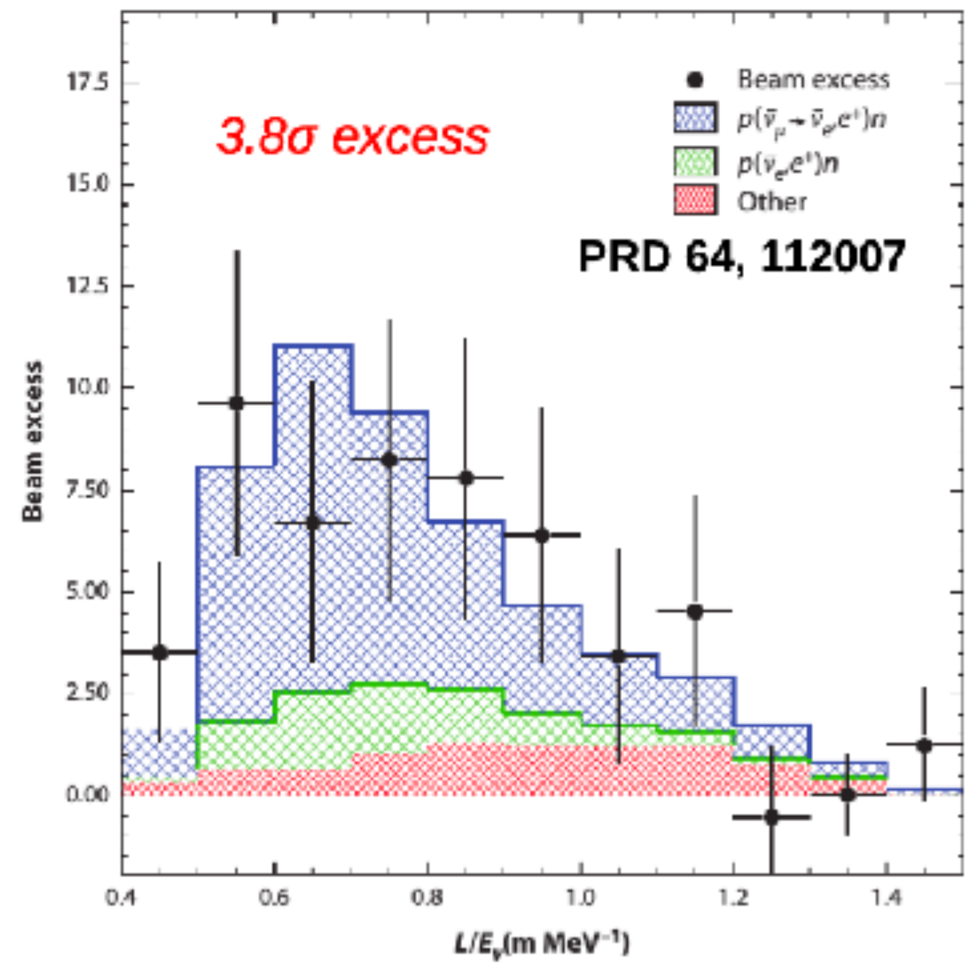
MiniBooNE detector

LSND

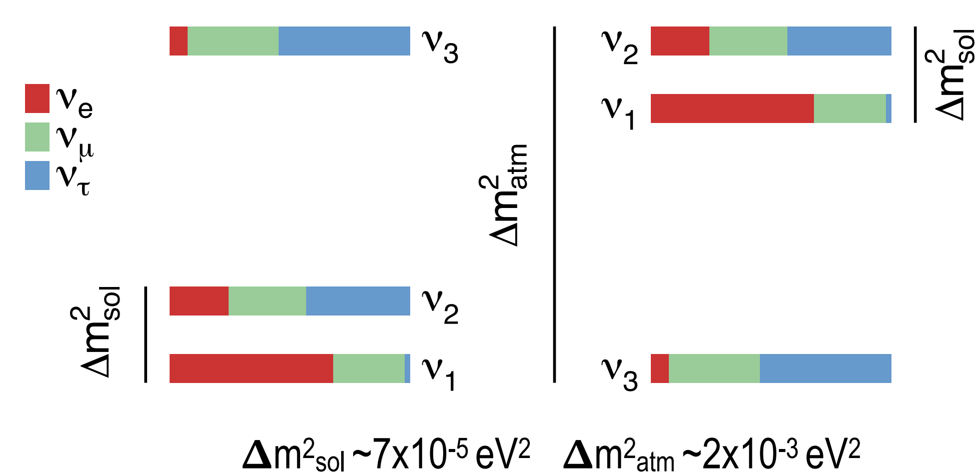
- Liquid Scintillator Neutrino Detector (LSND) at Los Alamos National Laboratory.

- Antineutrinos from μ^+ decay at rest
  ($\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$)
  30m baseline, 0.8 GeV neutrino beam energy.

- In 1995, LSND saw an excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation events at energies ~50 MeV (L/E ~1m/MeV)



- $\bar{\nu}_e$ excess observed:
  87.9 ± 22.4 ± 6.0 events consistent with $\bar{\nu}_e + p \rightarrow e^+ + n$ above expected background.



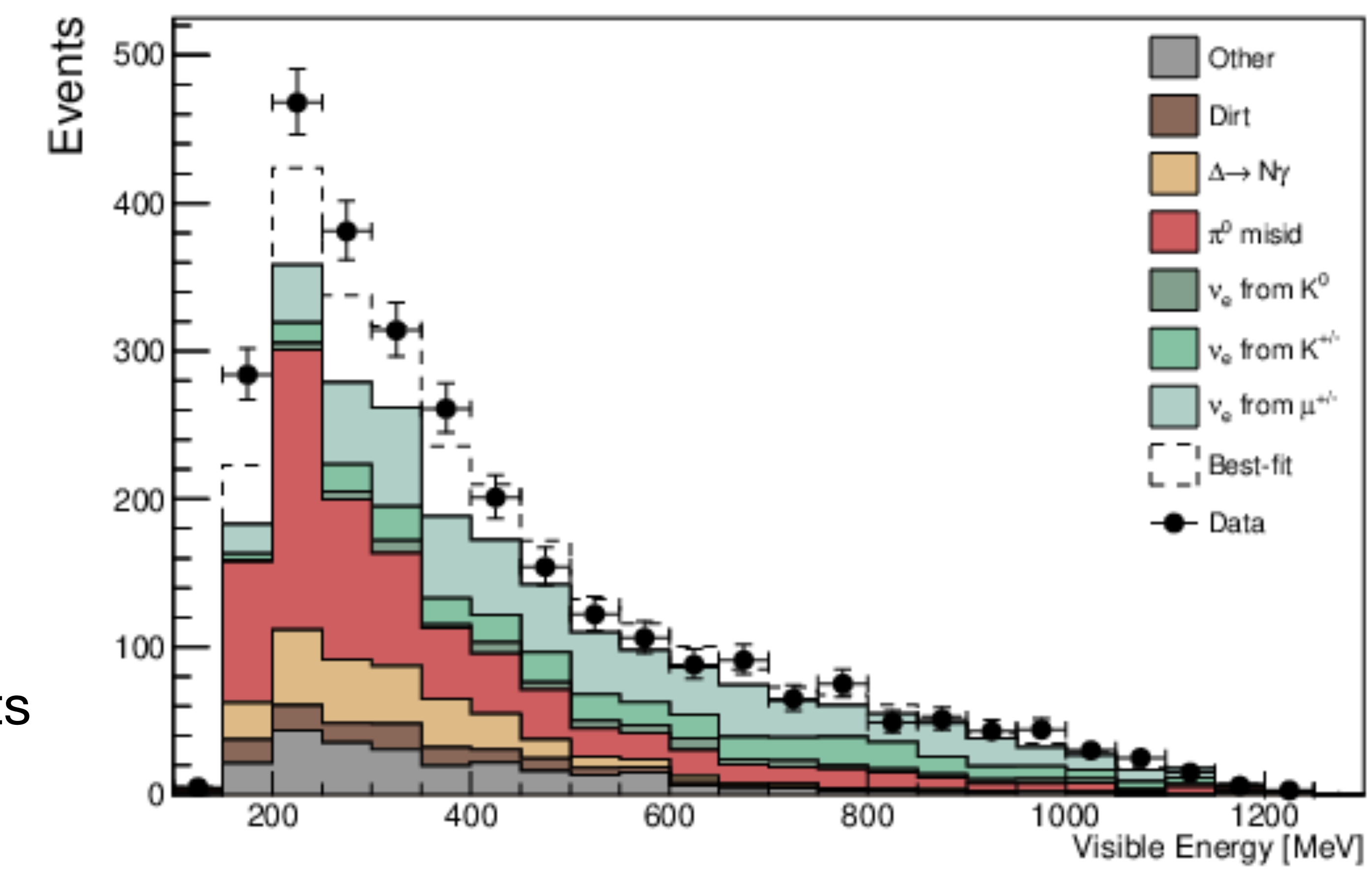
- If interpreted in a 2 neutrino oscillation model then most favoured oscillation region is a band in Δm^2 in the ~eV^2 range

- If excess is truly electron anti-neutrinos from oscillation then could be evidence of a 3+N sterile neutrino theory

MiniBooNE

- Spherical Mineral Oil (CH2) Cherenkov Detector at Fermilab.
- Booster Neutrino Beam (BNB) provides (mostly muon) neutrinos.
- MiniBooNE was built at a similar L/E as LSND to test its anomaly.
- With data collected from 2002 to 2019, sees a 4.8σ excess of ν_e candidate events
    - energies of about 200-500 MeV
    - forward-going angles
- Neutrino and anti-neutrino final fits consistent with LSND allowed regions.

MiniBooNE ν_e



The MiniBooNE neutrino mode visible energy distributions, corresponding to the total 18.75 × 10^{20} POT data in the 200 < E_ν^{QE} < 1250 MeV energy range, for ν_e CCQE data and background. 10.1103/PhysRevD.103.052002

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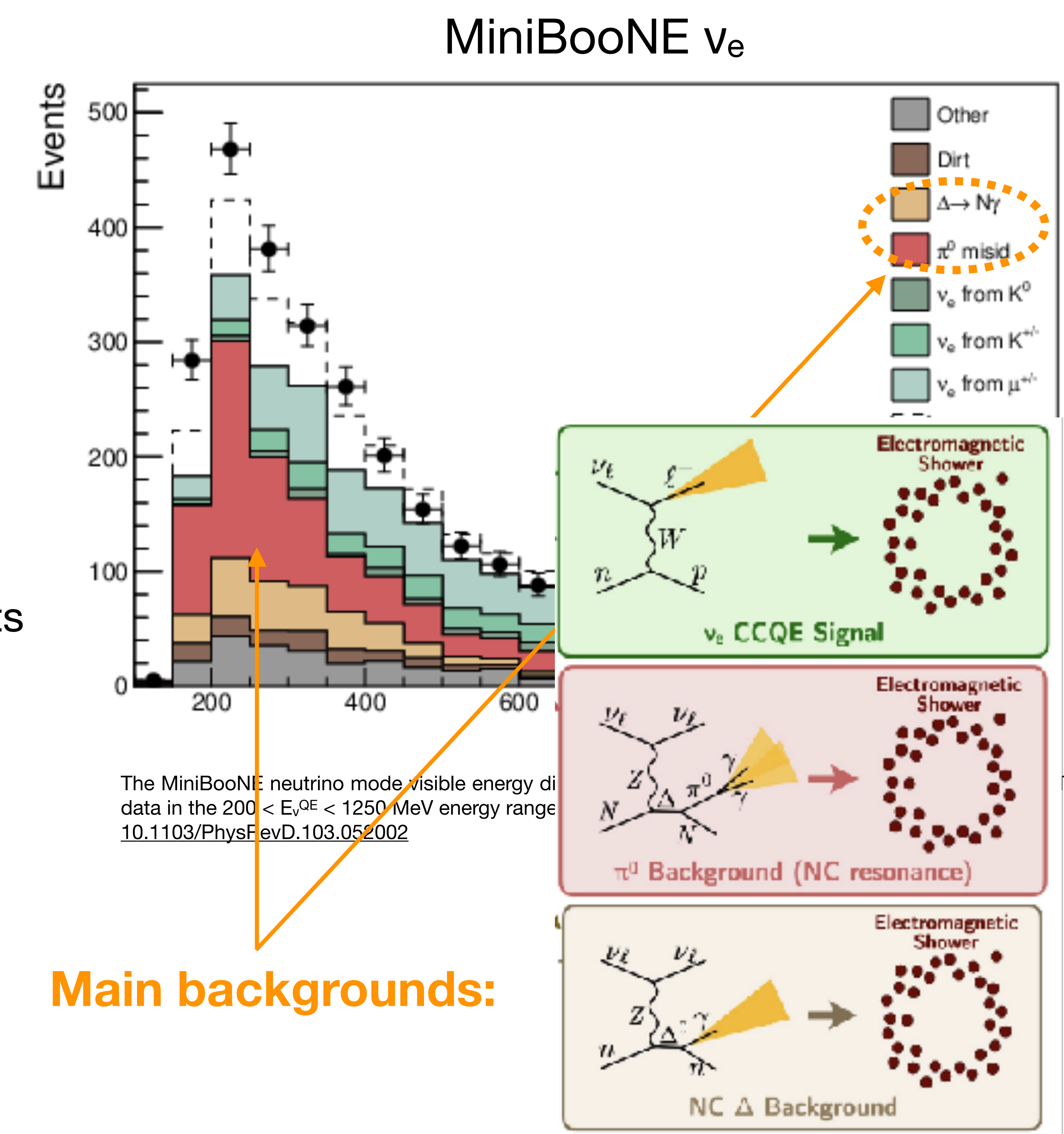
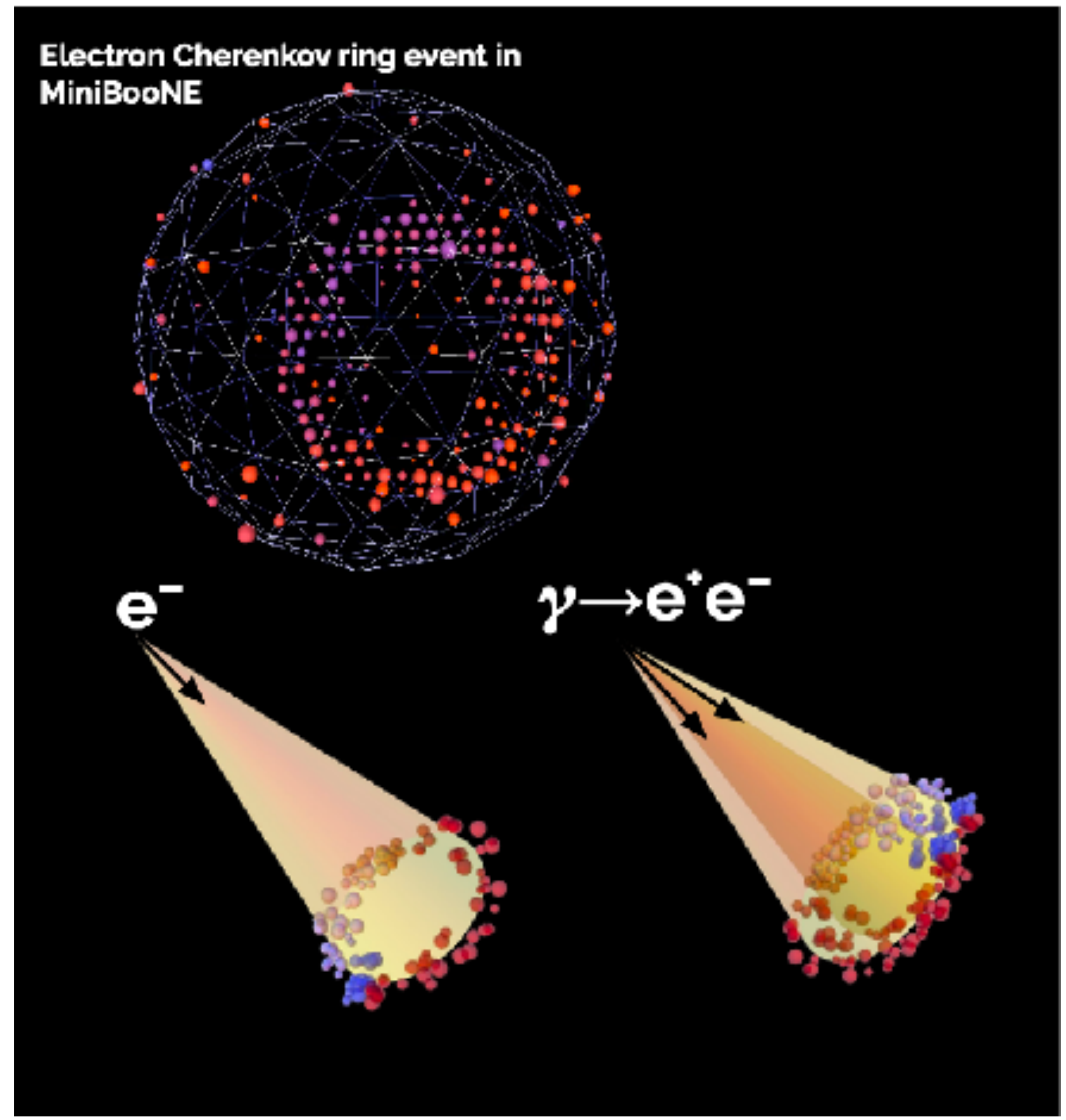


The MiniBooNE neutrino mode visible energy di... data in the 200 < E_ν^{QE} < 1250 MeV energy range... 10.1103/PhysRevD.103.052002

Cherenkov detectors challenge

- e^- vs γ discrimination extremely difficult by Cherenkov detectors.
- Open question:
  How can we resolve the nature of the MiniBooNE e-like signal a.k.a. Low Energy Excess (LEE)
- A technology capable to do Electron/Gamma discrimination needed ⇒ LArTPCs



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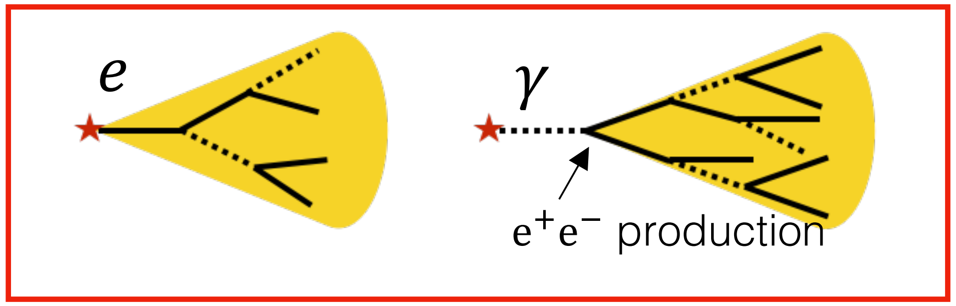
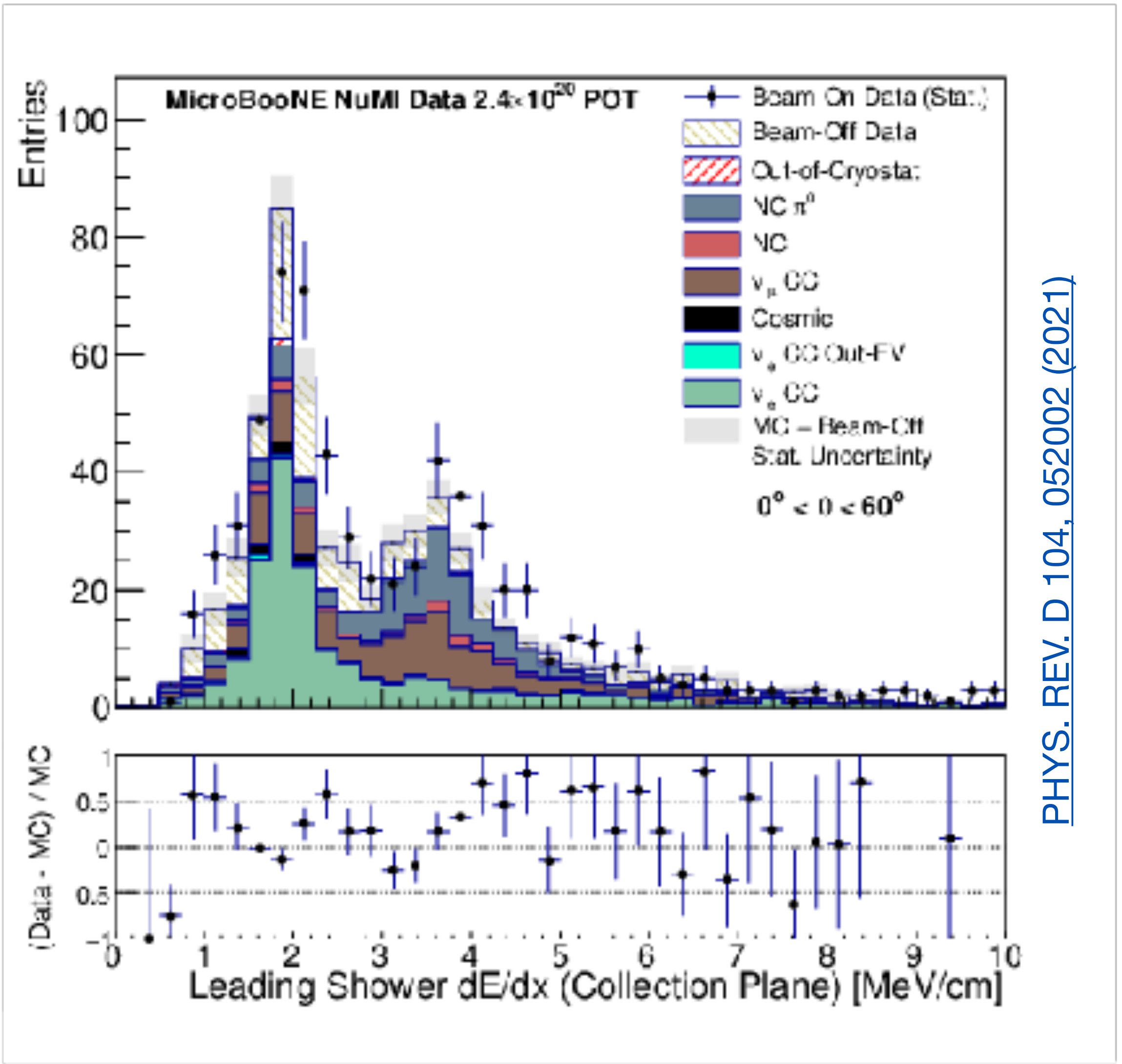
Assembly of the MicroBooNE TPC

Why LArTPCs?

- Capable of identifying different species of particles and reconstructing 3D images with fine-grained information. Neutrino vertex, particle flow, track vs. shower…

- Electron vs gamma discrimination:



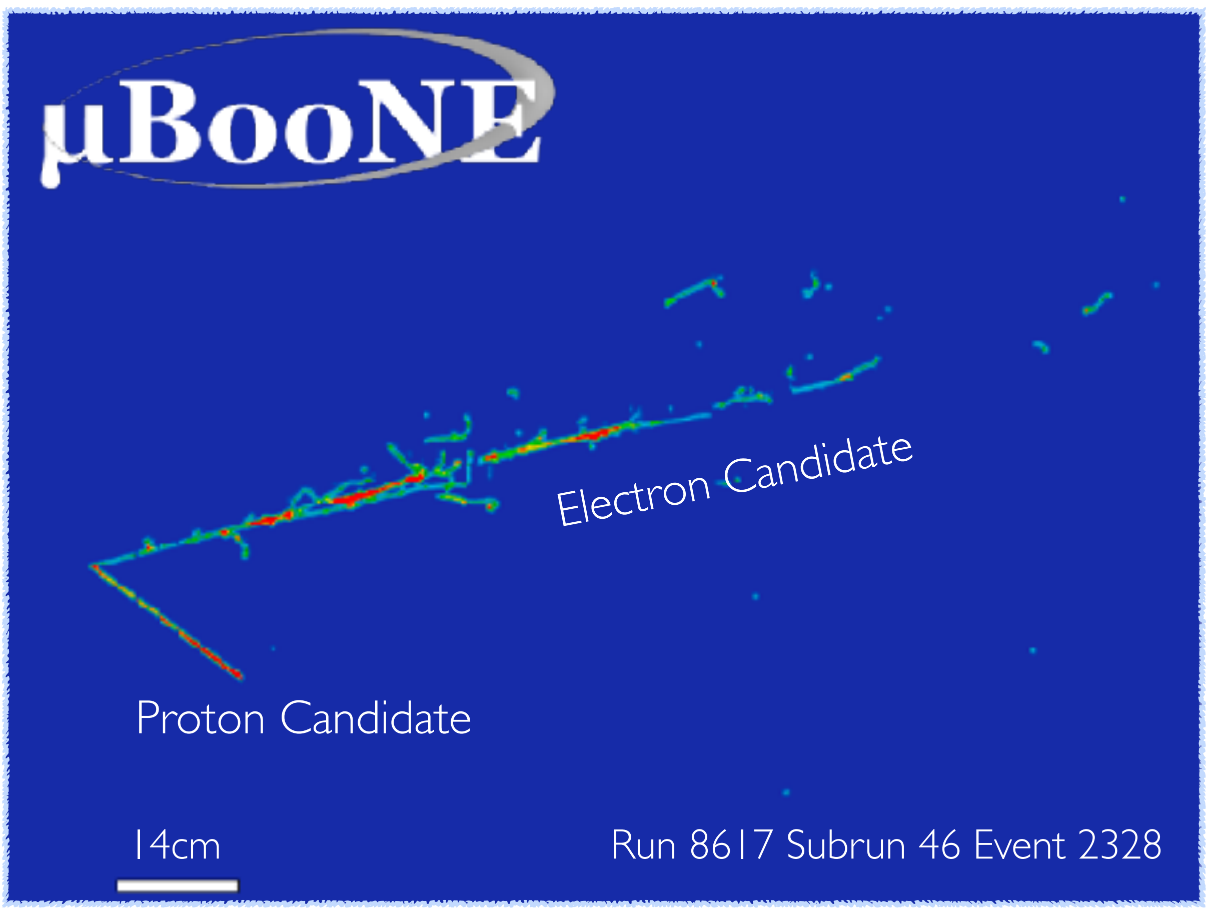


PHYS. REV. D 104, 052002 (2021)

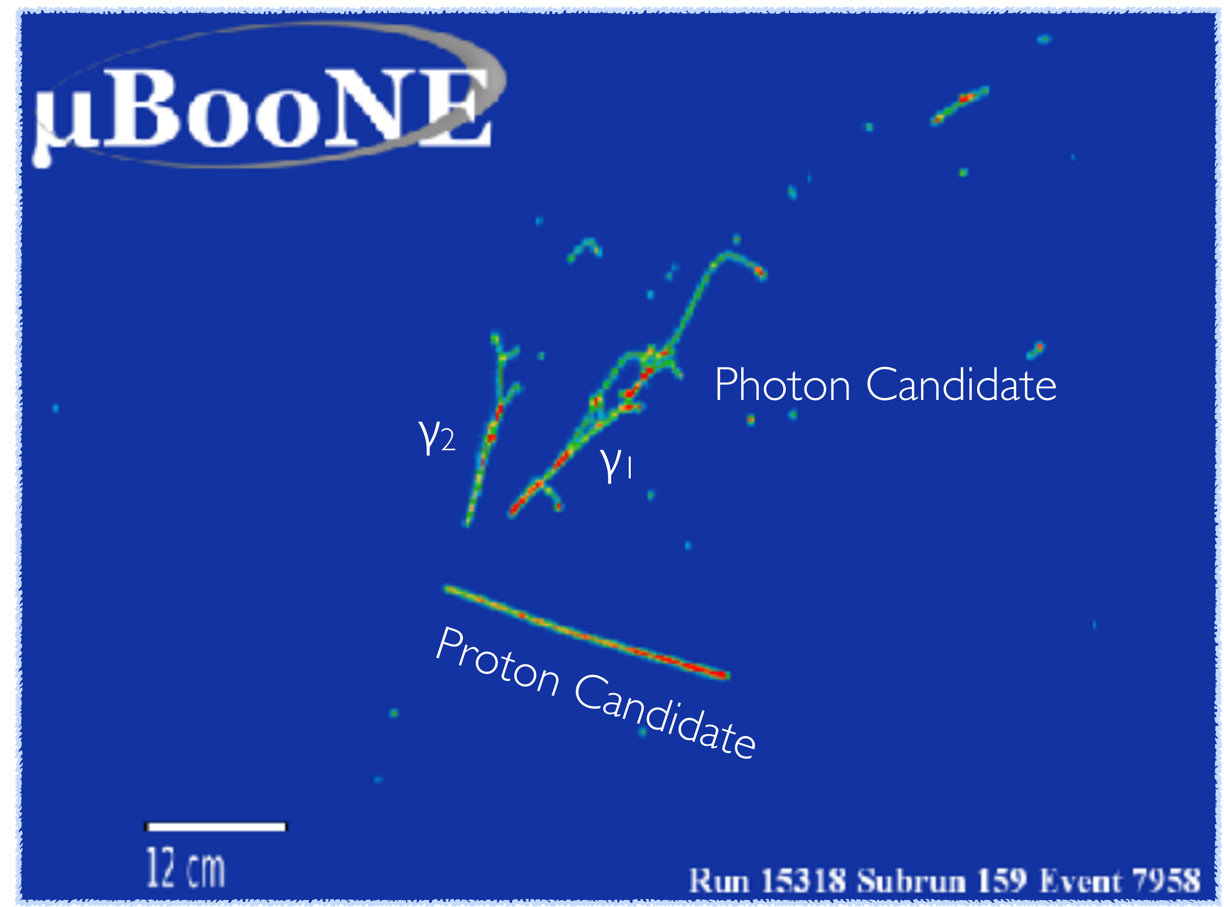
  - dE/dx at start of shower
  - Conversion gap

e^- / γ separation in LArTPCs

ν_e Charged-Current (CC) Candidate

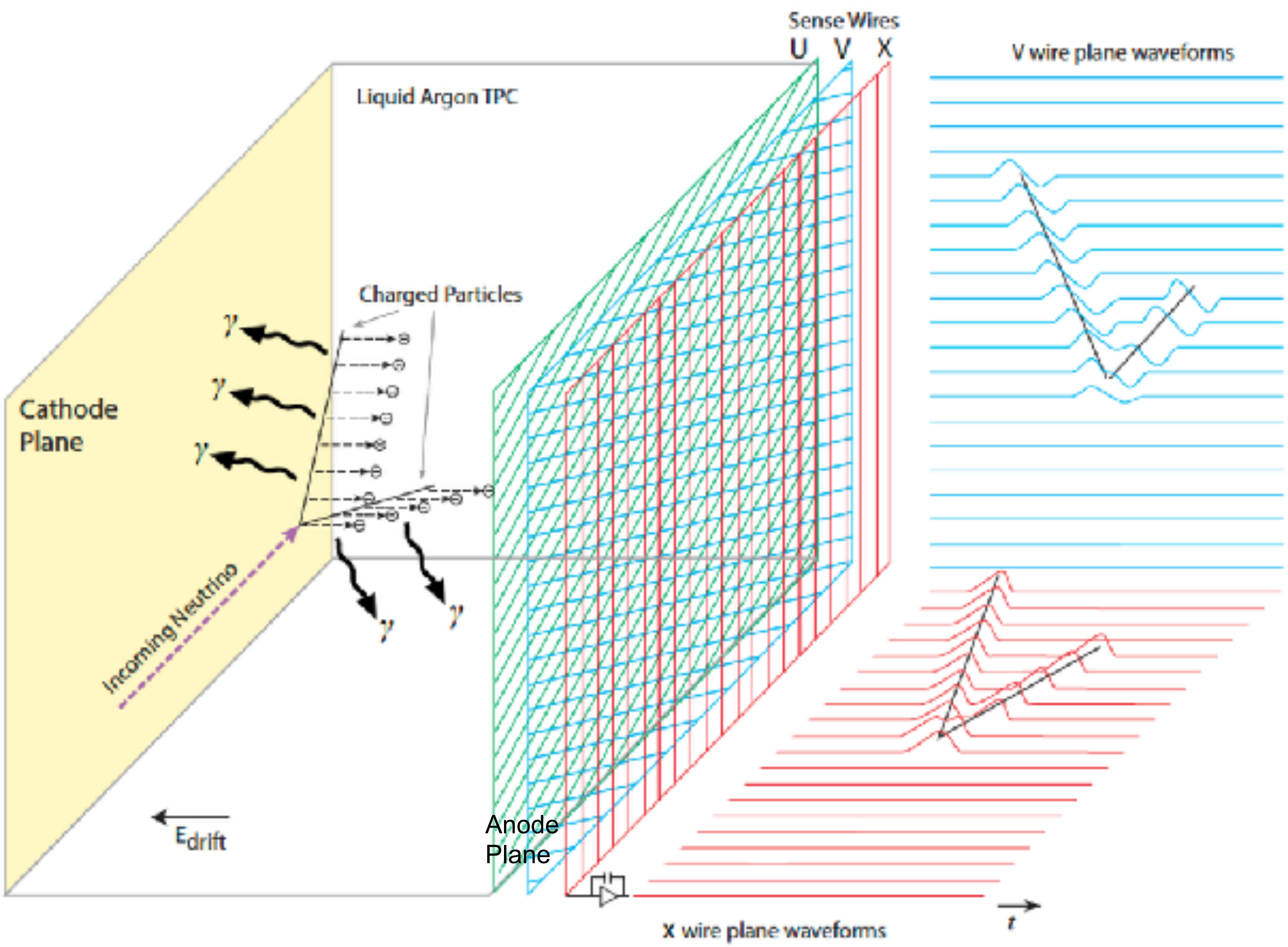


$\nu_\mu \pi^0$ Neutral-Current (NC) Candidate



Operation of LArTPC

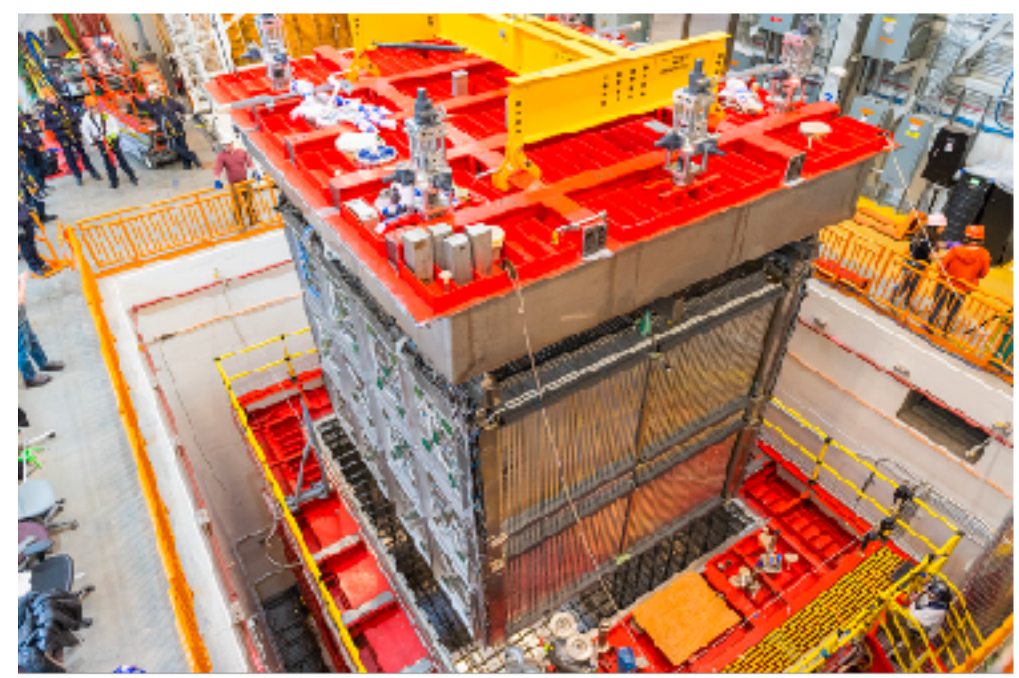
Homogeneous target that combines large mass with accurate spatial and calorimetric reconstruction.



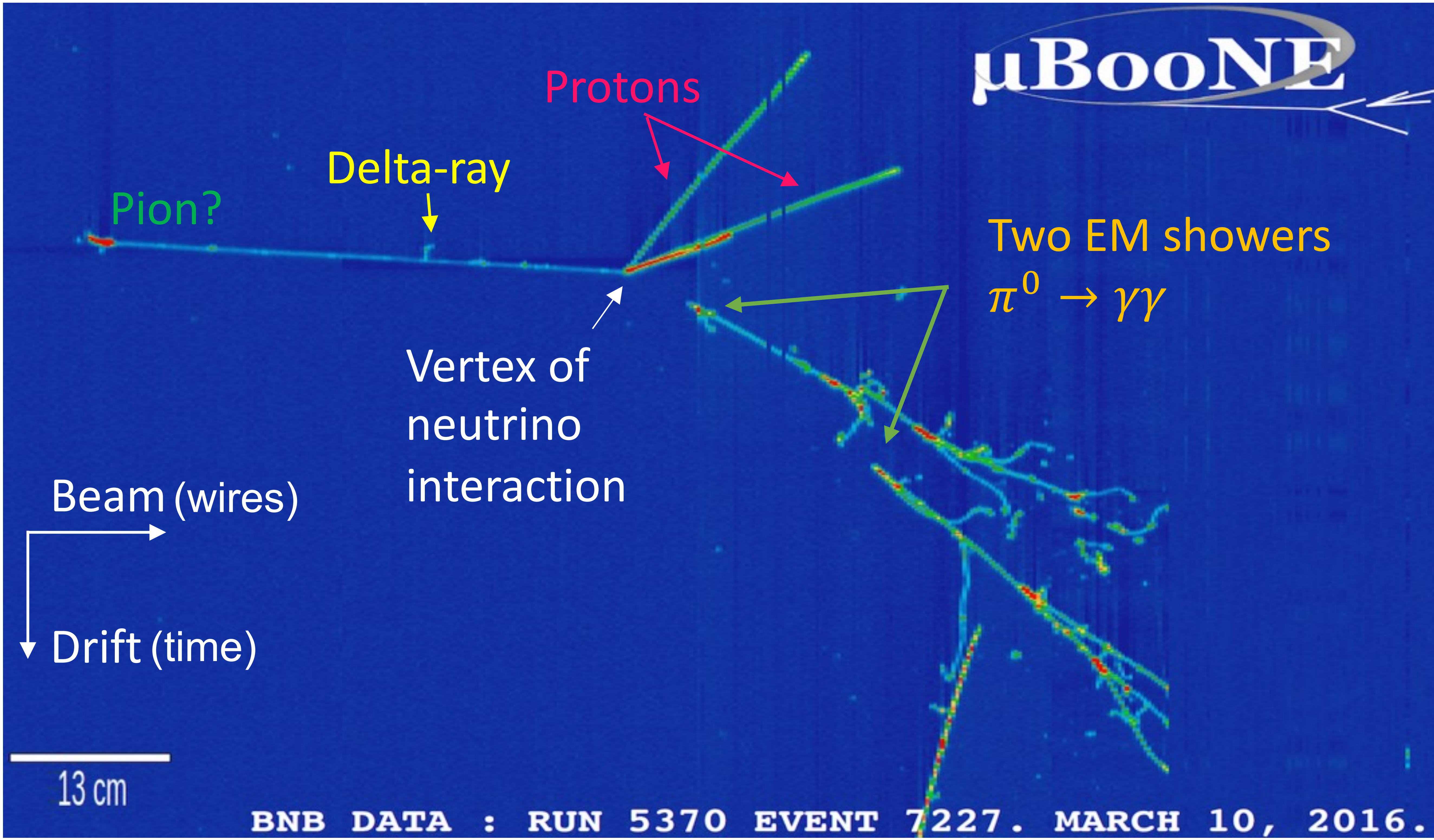
- Ionisation electrons:
  Drifted (E) towards wires planes.
  Response time = drift time (~ ms)
- λ = 128 nm scintillation light:
  Response time O(10ns), provides signals for timing/triggering.
- 3D image reconstruction by combining coordinates on different wire planes at the same drift time.

Features

- LAr : large interaction rate
- Modular and scalable
- Nearly fully instrumented
- Millimetre resolution
- Fully active calorimeter
- Charge collection millisecond time-scale
- Ar Scintillation light collection



Liquid Argon Time Projection Chambers



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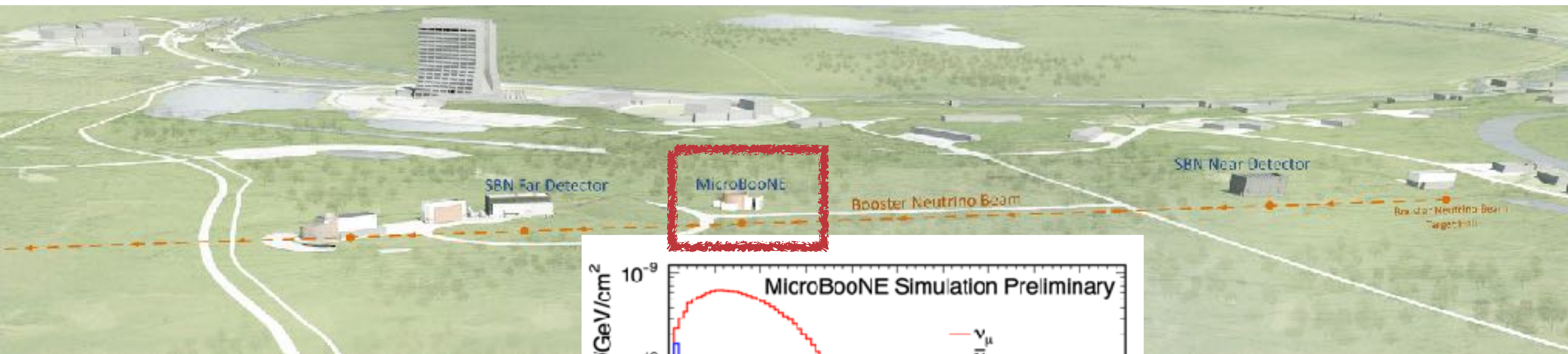
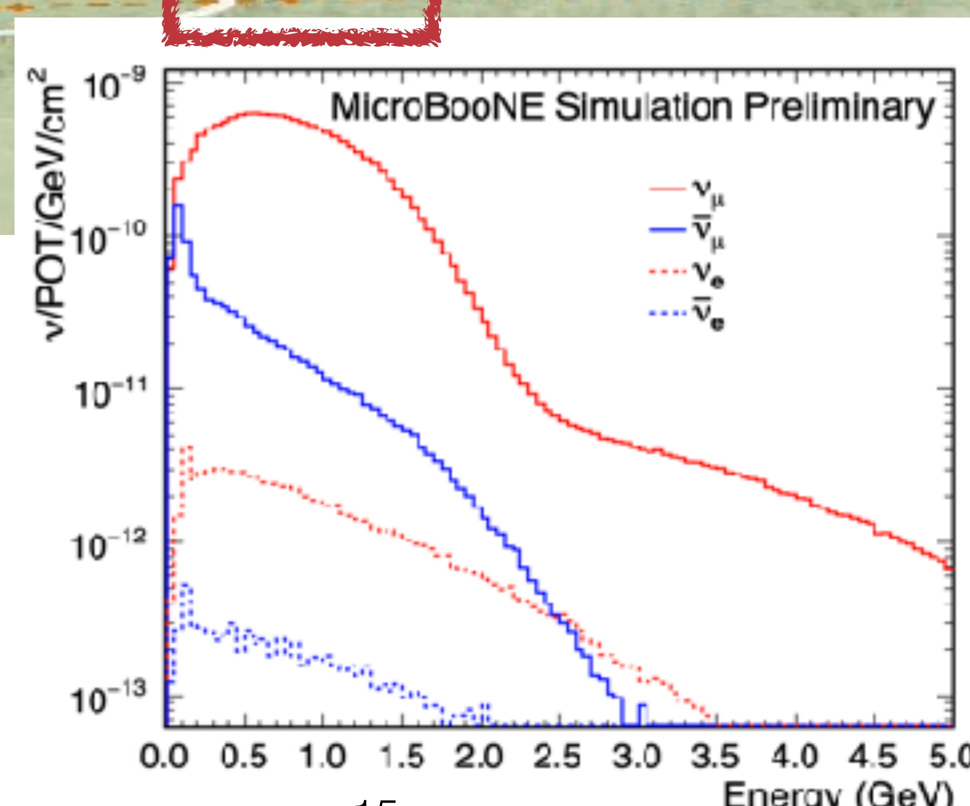
The MicroBooNE cryostat being moved into the Liquid-Argon Test Facility (LArTF).

MicroBooNE at Fermilab

A multi-detector facility on the Booster Neutrino Beam at Fermilab using the same neutrino beam,

- Neutrino beam from pion decay-in-flight mostly. Well-known beam, same as MiniBooNE (PRD 79, 072002).
- Main goal to test the miniBooNE signal nature (MicroBooNE)





BNB ν_μ: 8 GeV protons,
ν energy peak at ~600 MeV

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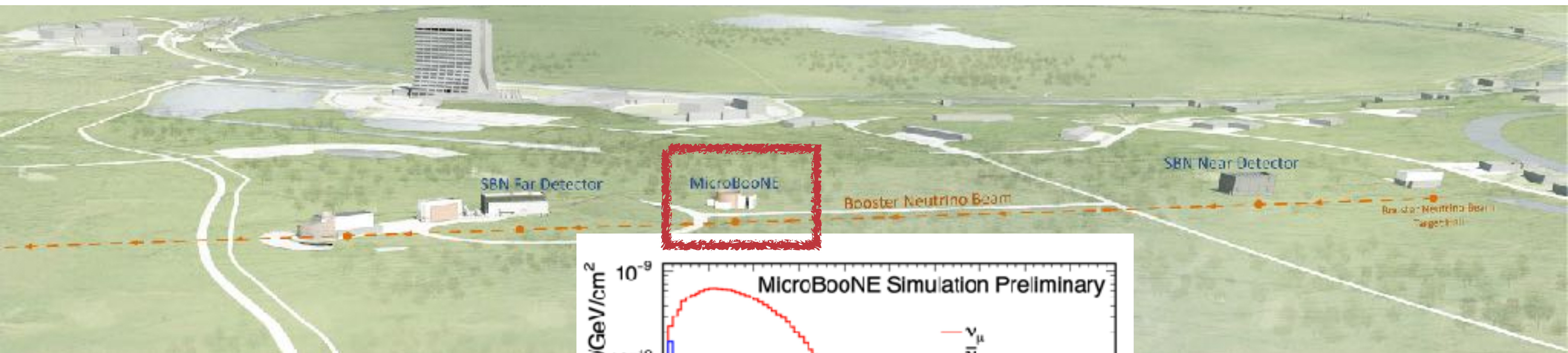
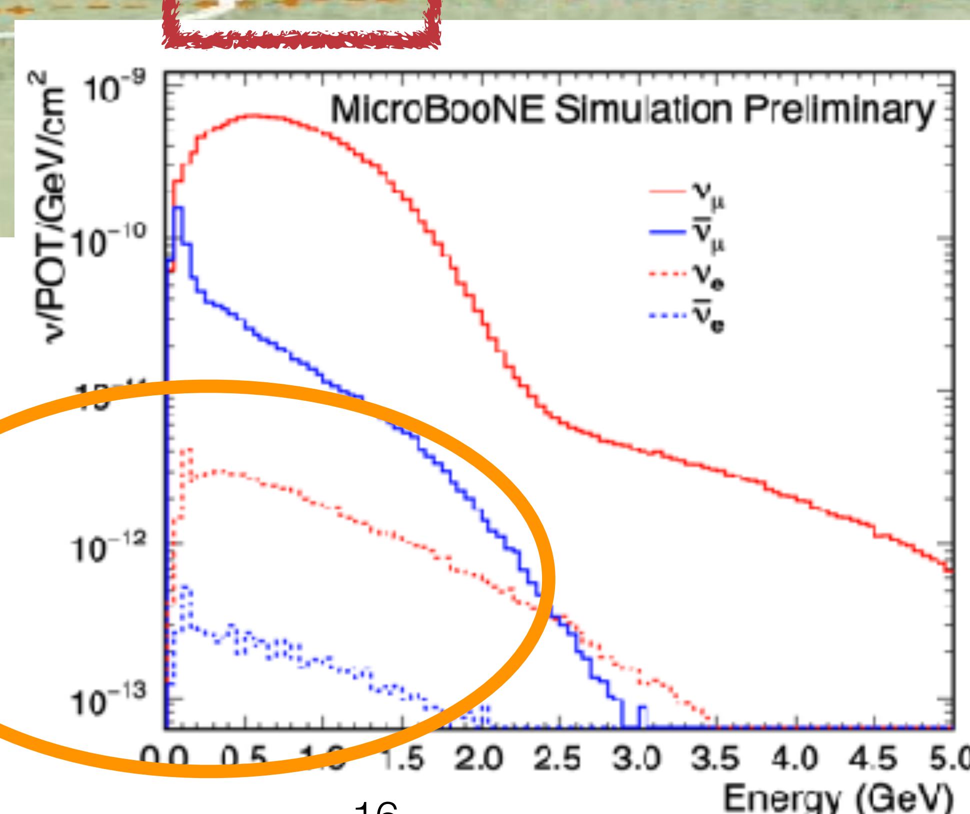
- Main goal to test the miniBooNE signal nature (MicroBooNE) and the sterile sterile neutrino existence (SBN)





BNB ν_μ: 8 GeV protons,
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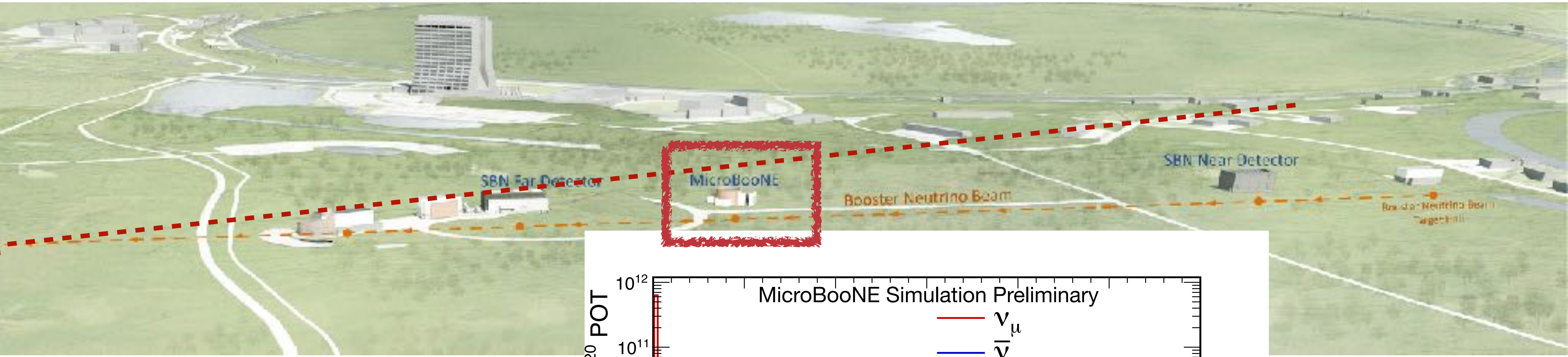
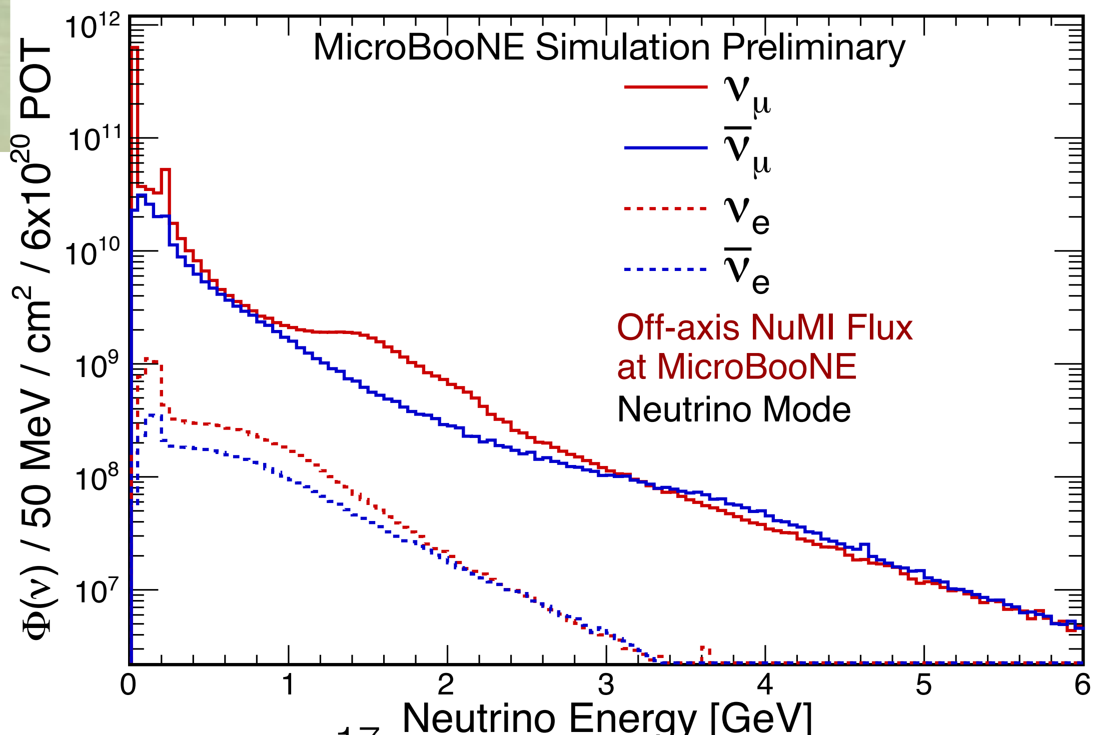
MicroBooNE at Fermilab

A multi-detector **and multi-beam** facility at Fermilab using the same neutrino beam, nuclear target .

- In addition to the on-axis BNB beam, MicroBooNE sees the NuMI beam at an off-axis angle of 8°



NuMI ν_μ: 120 GeV protons



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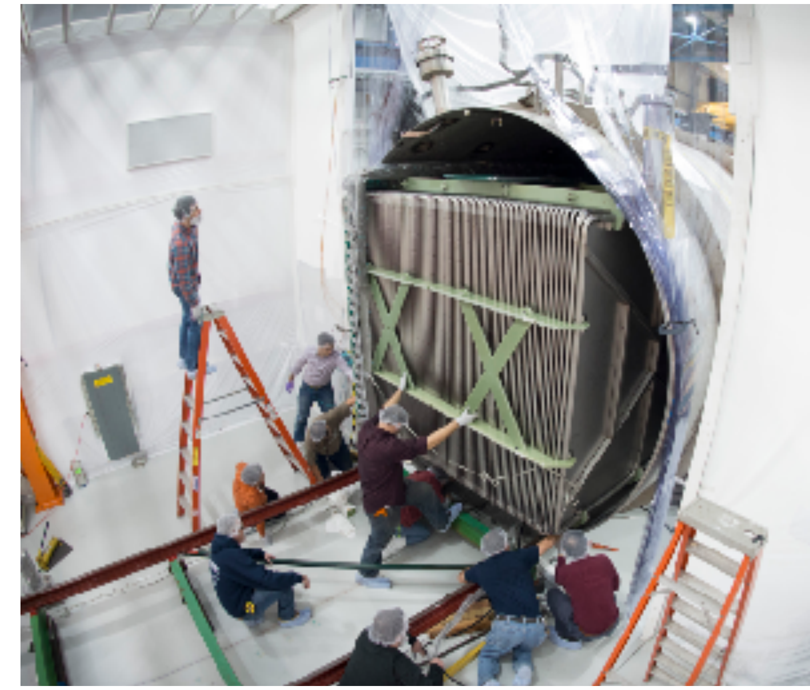
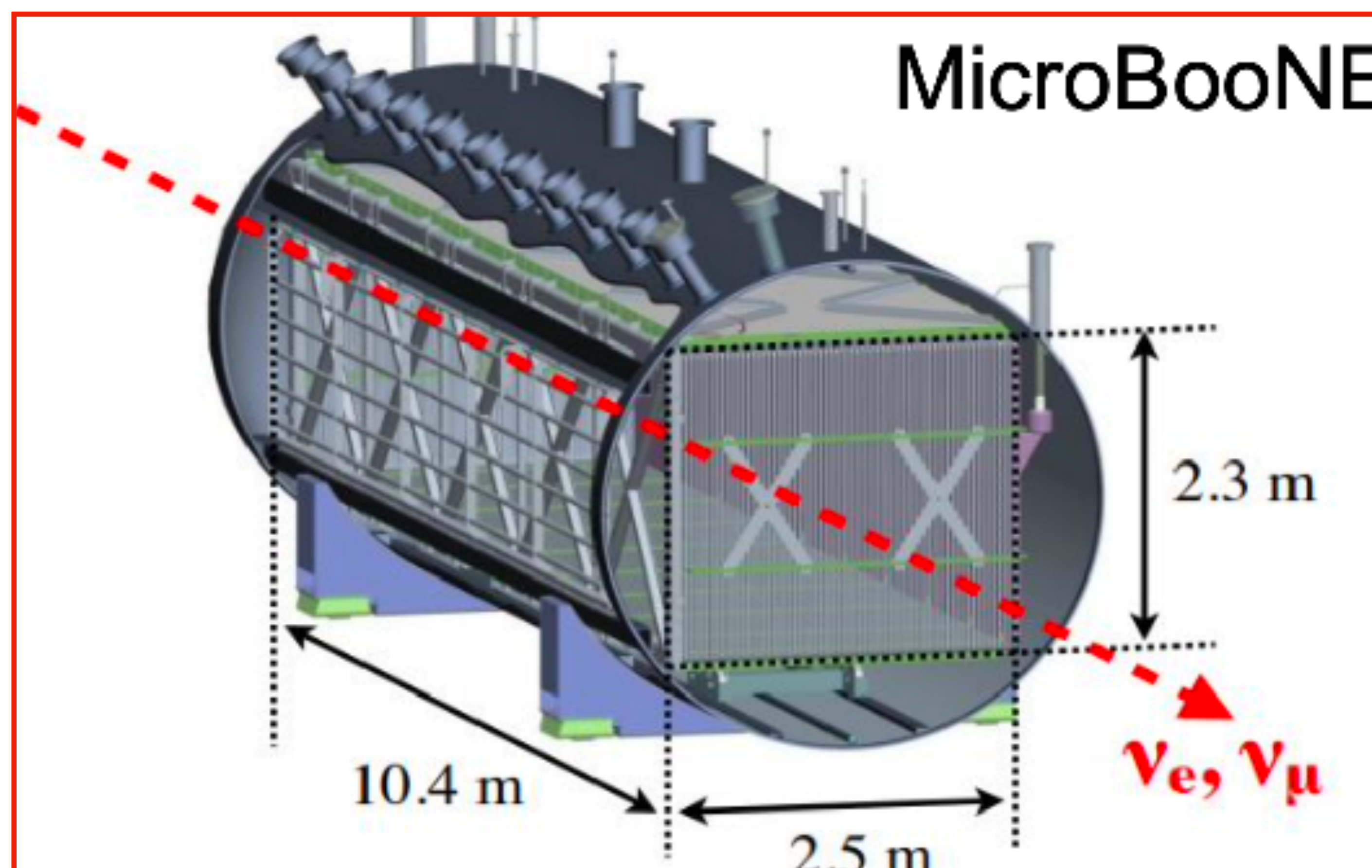
The MicroBooNE experiment

MicroBooNE detector



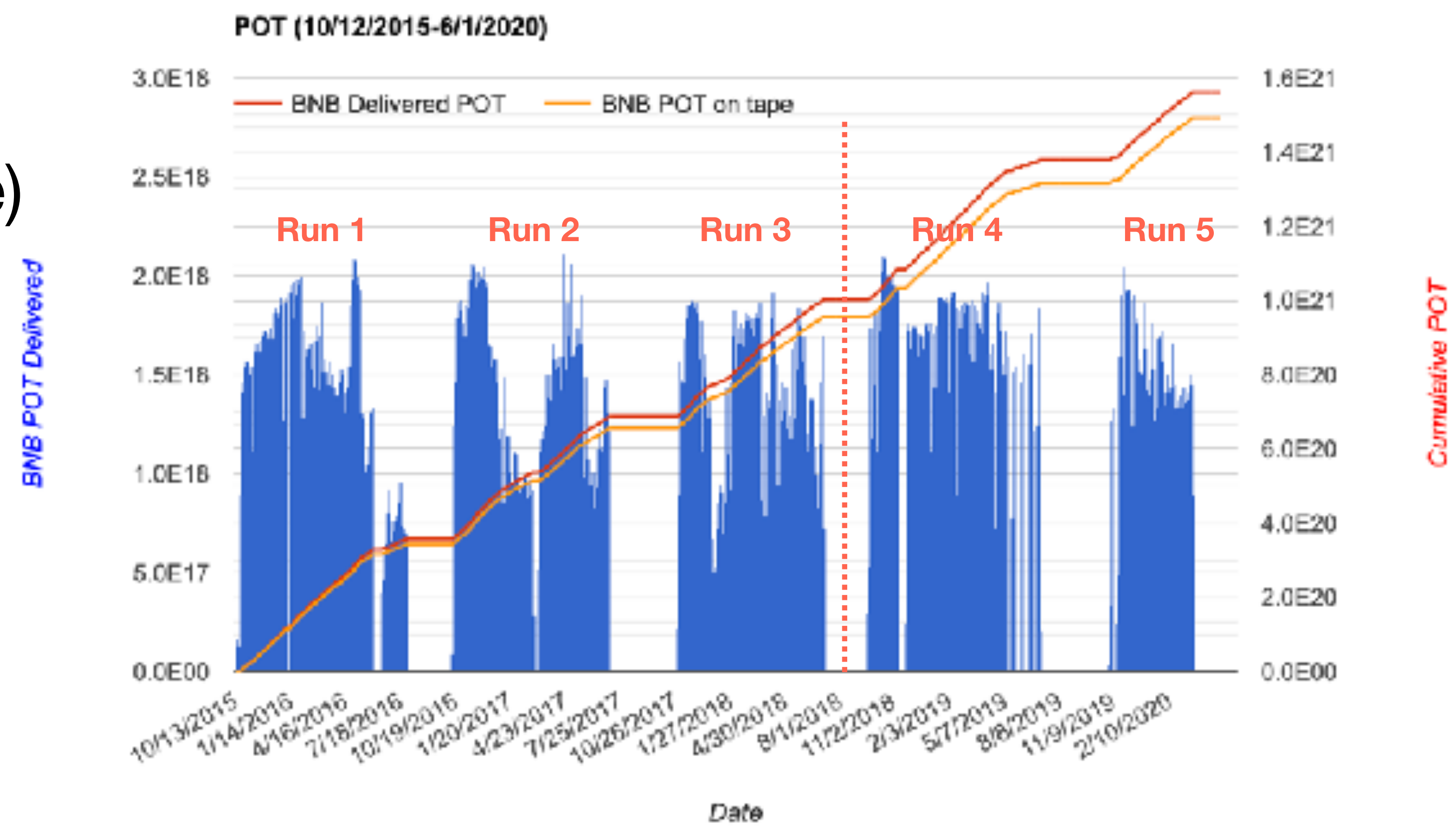
- MicroBooNE is a surface-level, 85 active LAr tonne (10×2.5×2.5 m3) LArTPC neutrino experiment
- Situated ~470m downstream Fermilab's Booster Neutrino Beamline (BNB)
- Collected data from 2015 to 2021 The largest sample of neutrino interactions on argon in the world.
- Scintillation light collected by 32 PMTS and ionization charge by 3 wire planes.



The MicroBooNE experiment

MicroBooNE goals

- Low-Energy Excess searches (MiniBooNE like signal nature)
- other Exotic BSM physics
- Improving our understanding of ν-Ar interactions
- LArTPC hardware and software R&D



- Recent results based on 6.80×10^{20} protons-on-target (POT) from Runs 1-3
- Analysing remaining 1⁄2 of our data from Runs 4-5 is well underway!

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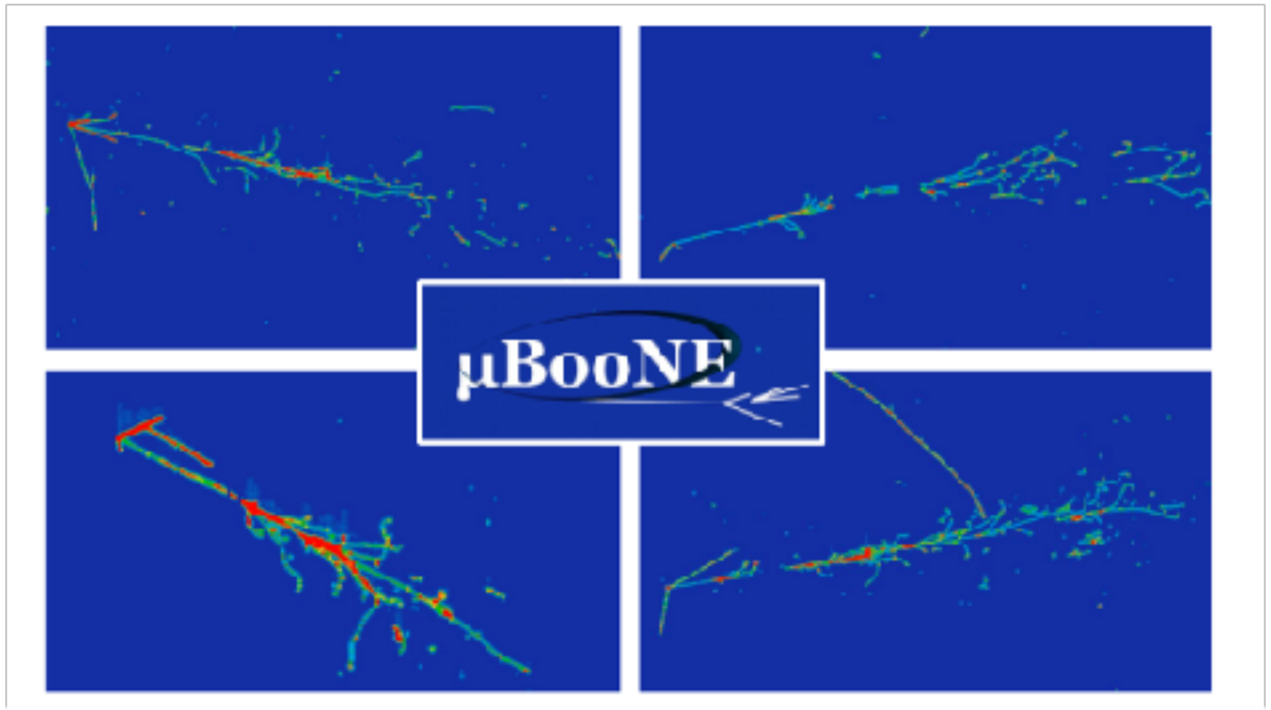
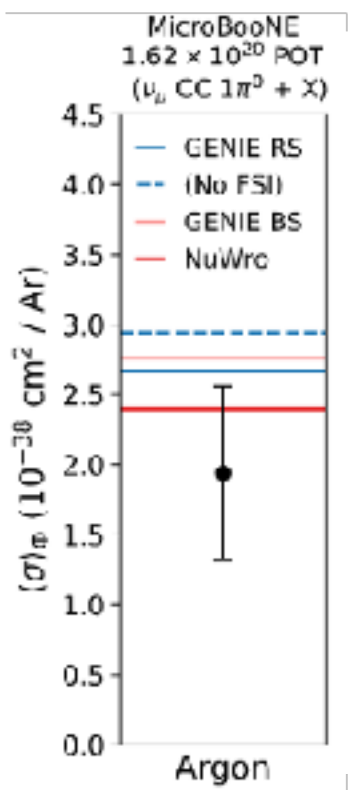


MiicroBooNE event displays

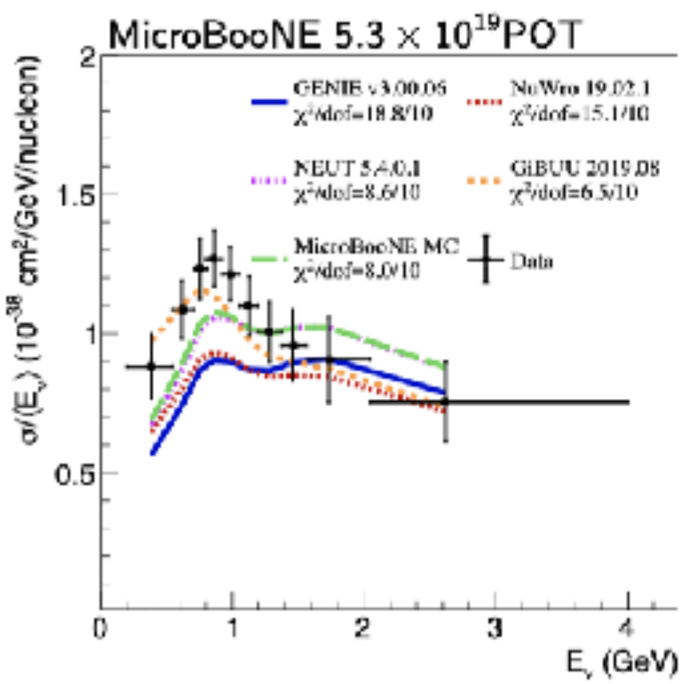
Measuring neutrino interactions

- Any discovery in the neutrino sector requires detailed understanding of neutrino interactions.
- By leveraging the power of LArTPC technology, MicroBooNE has developed an extensive cross-section program to study inclusive and exclusive neutrino-argon with the BNB to test ν_μ and NuMI to test ν_e



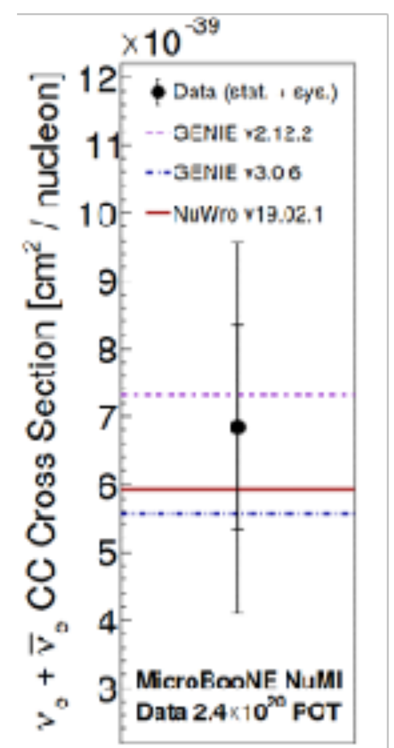
ν_μCC π^0 production

[Phys. Rev. D99, 091102(R) (2019)](https://doi.org/10.1103/PhysRevD.99.091102)



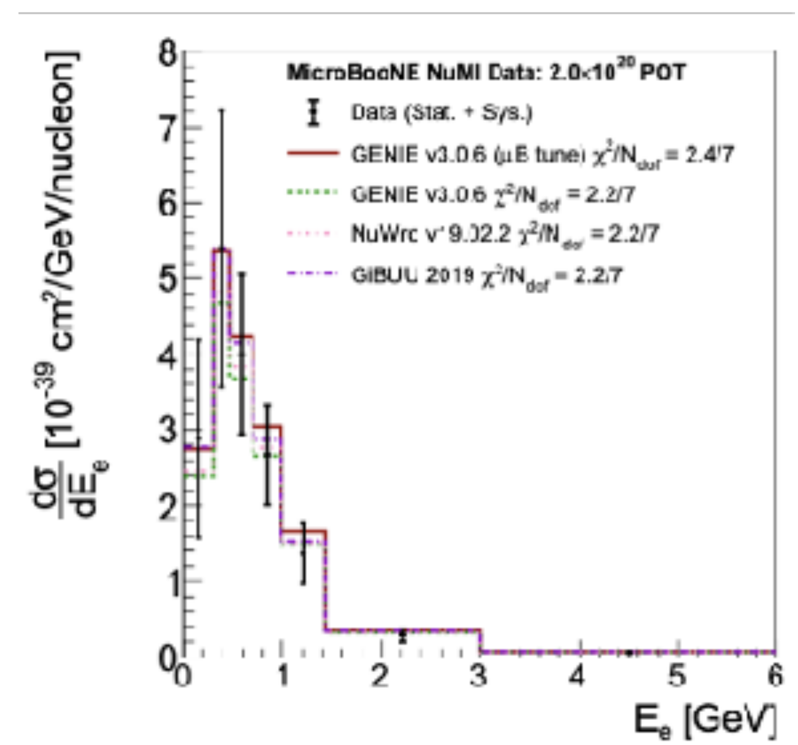
Energy dependent ν_μCC inclusive

[Phys.Rev.Lett. 128 (2022) 15](https://doi.org/10.1103/PhysRevLett.128.151801)



Flux Averaged
Inclusive ν_e+$\bar{\nu}_e$

[Phys. Rev. D.104.052002](https://doi.org/10.1103/PhysRevD.104.052002)

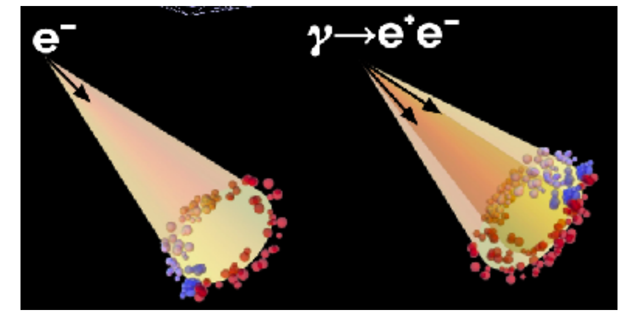


Inclusive $\nu_e + \bar{\nu}_e$ CC
differential in energy and angle

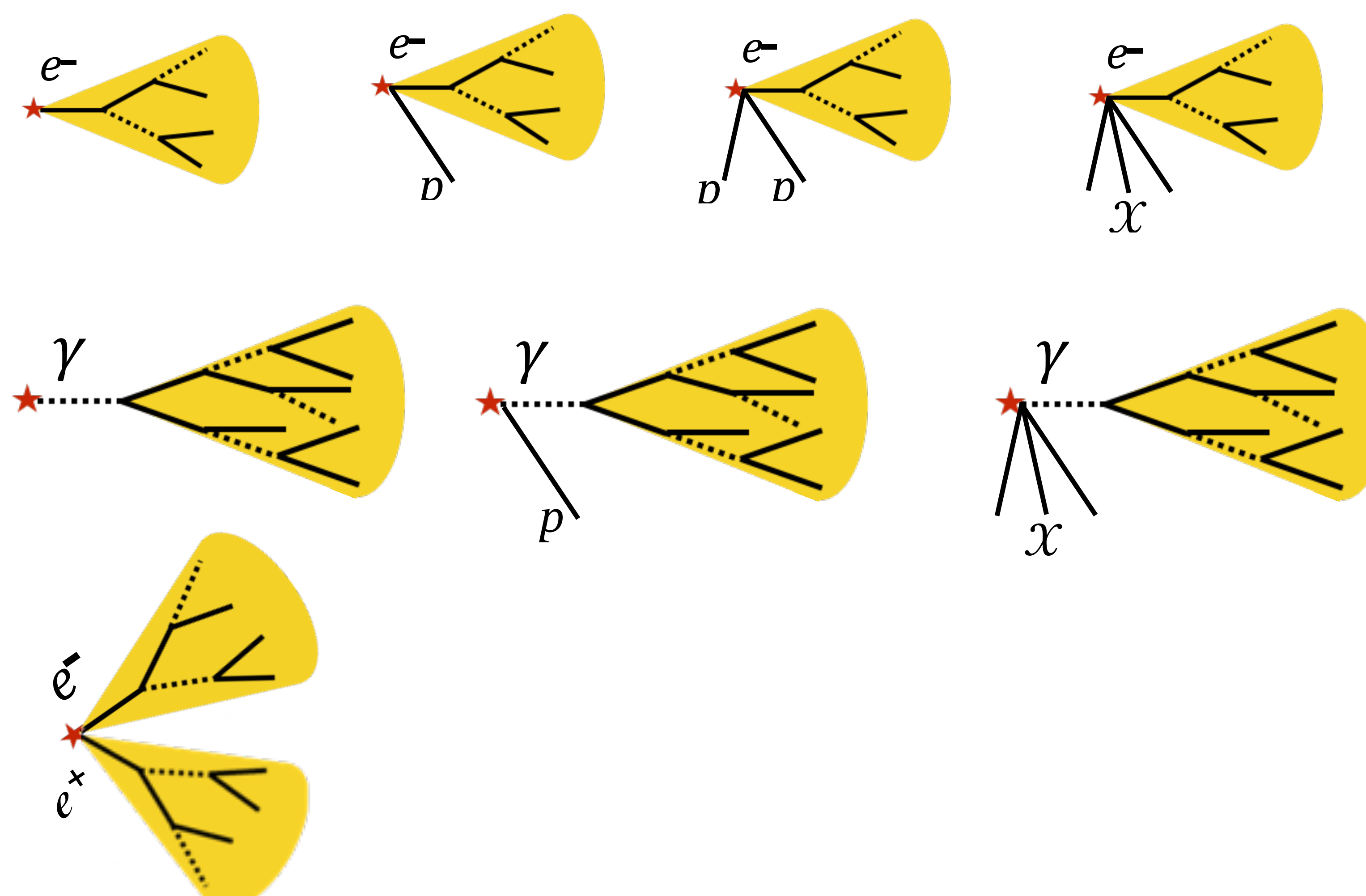
[Phys. Rev. D 105, L051102](https://doi.org/10.1103/PhysRevD.105.L051102)

Possible LEE Channels

Low-Energy Excess searches
(MiniBooNE like signal nature)



- 1e (Np / X)
  (oscillation)
- 1γ (Np / X)
  (nuclear backgrounds or BSM)
- e⁺ e⁻
  (BSM)



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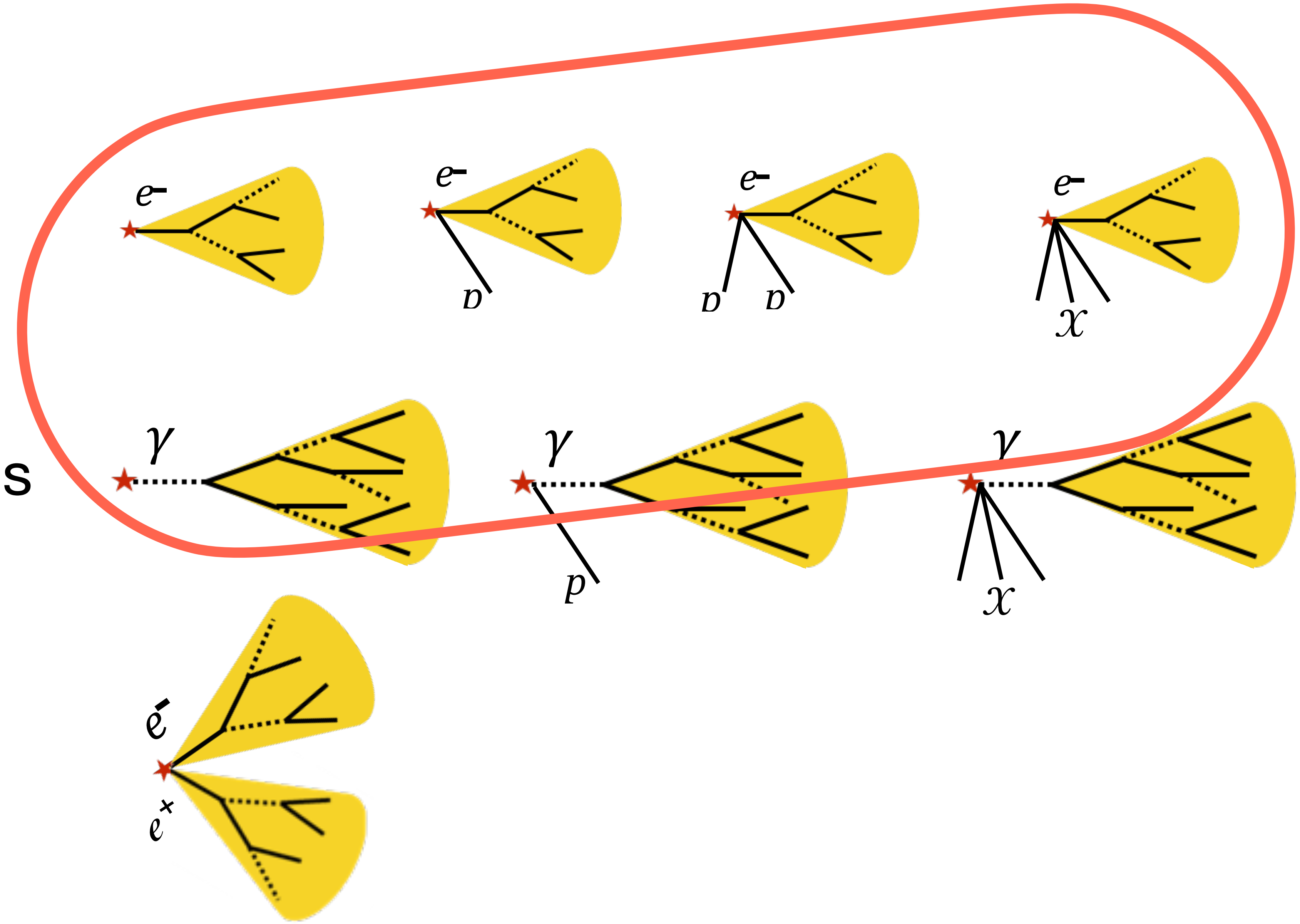
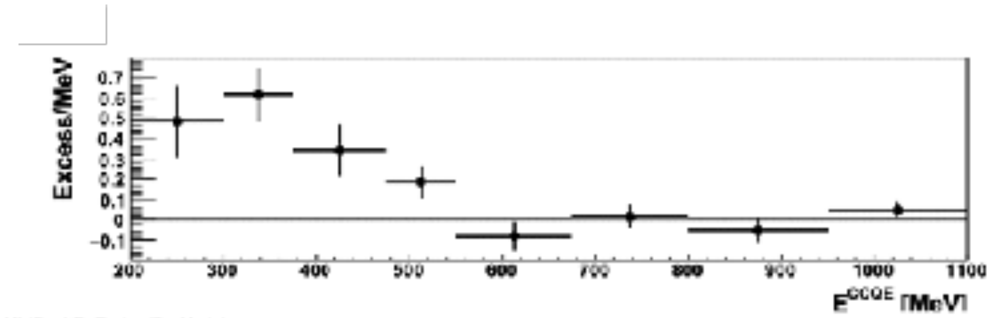
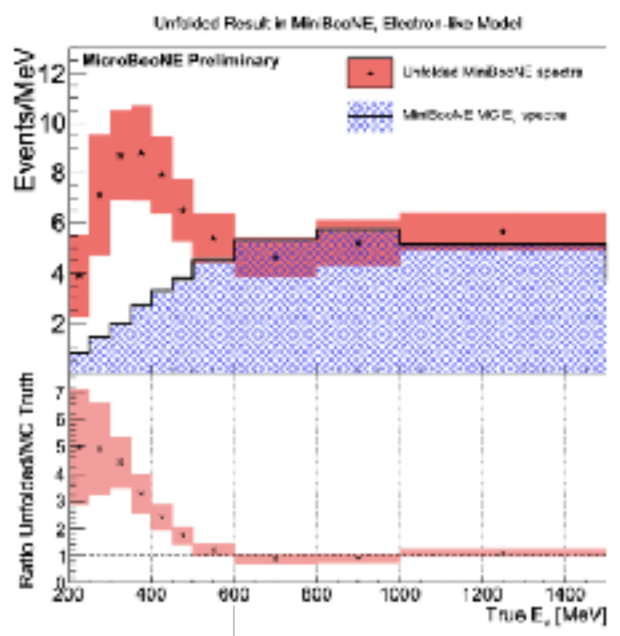


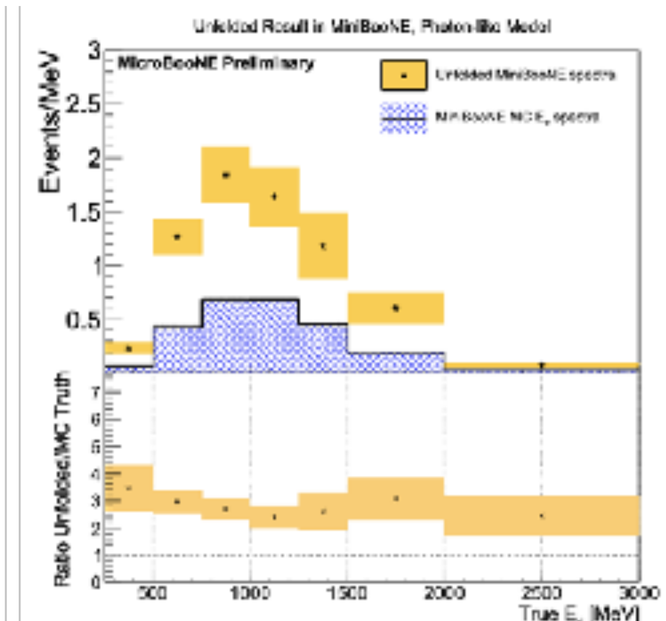
LEE signal modeling

1) Take background subtracted excess of data events in MiniBooNE

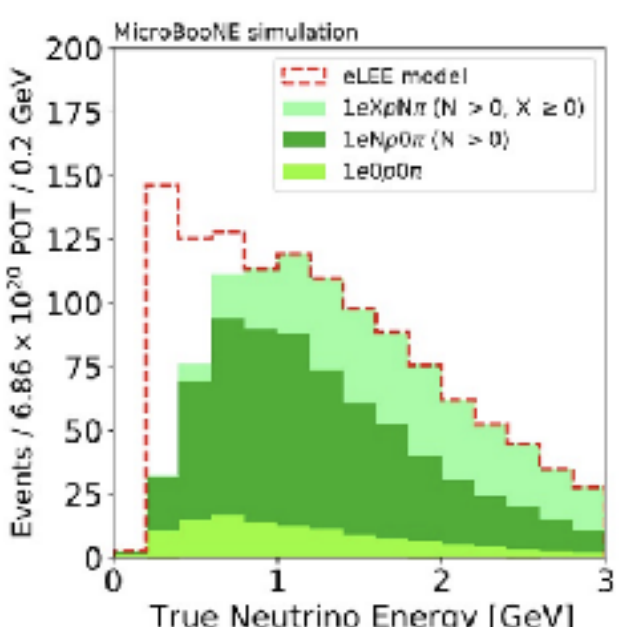


2 e) Assume excess is intrinsic ν_e & unfold to true energy

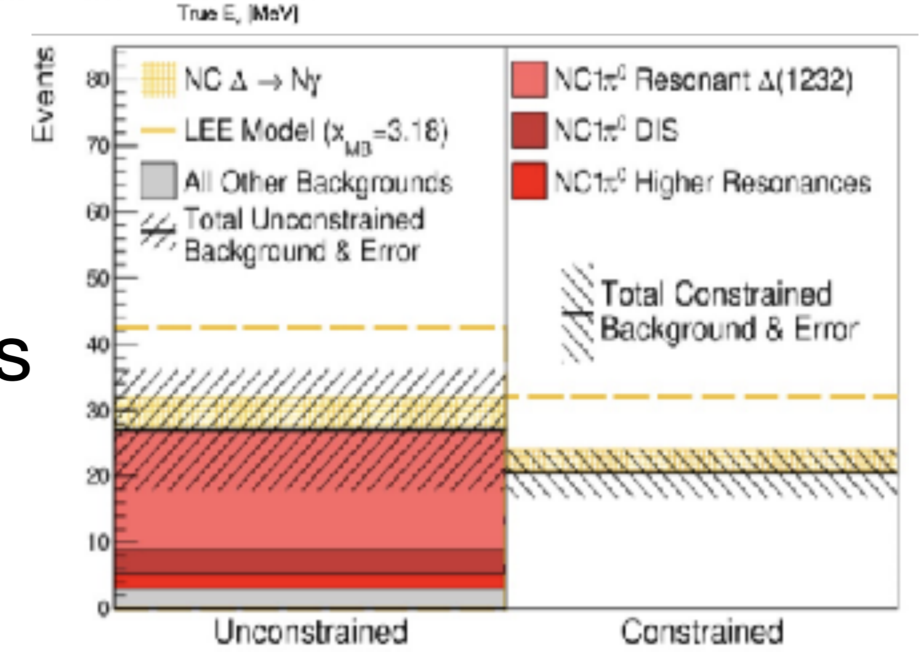




2 γ) Assume excess is $\Delta \rightarrow N\gamma$ & unfold to true energy



3) Test MicroBooNE analyses against this benchmark signal



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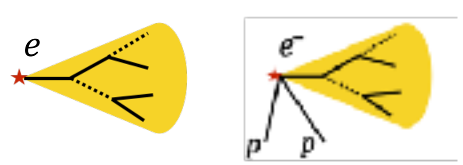
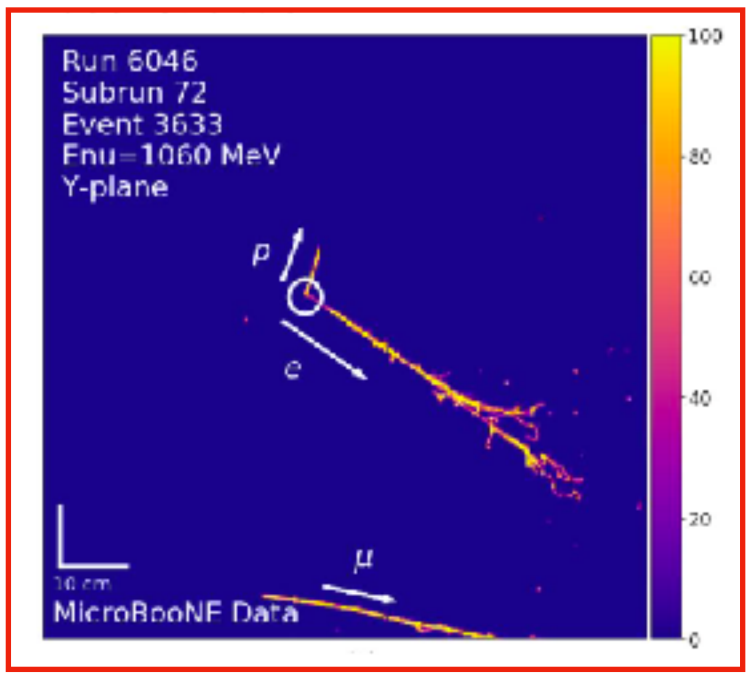
Low-Energy Excess (Electron) Results

Three independent ν_eCC searches targeting four different final states (1e0p, 1e1p, 1eNp, 1eX) each with different novel reconstruction approaches developed in MicroBooNE.

Semi-inclusive ν_e scattering no pions.
Pandora reconstruction



[1eNp0π] and [1e0p0π]



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

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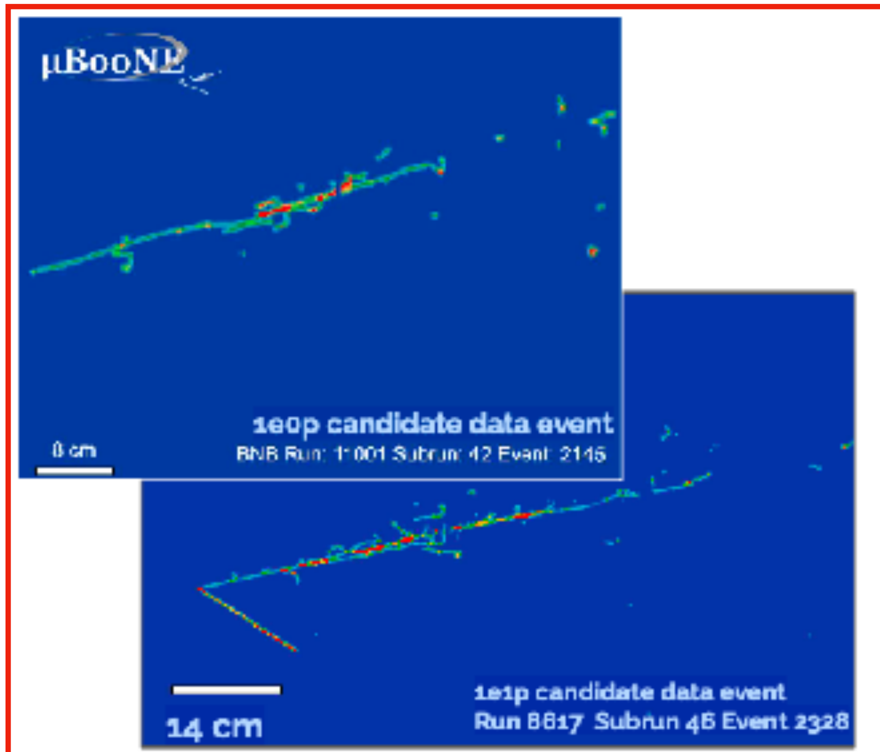
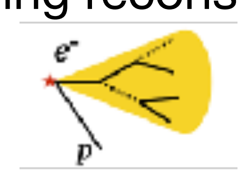
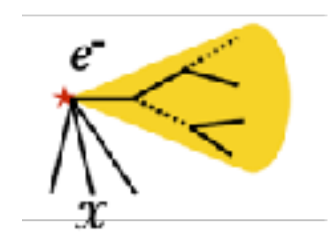


Exclusive 2-body CCQE ν_e scattering.
Deep-Learning reconstruction.



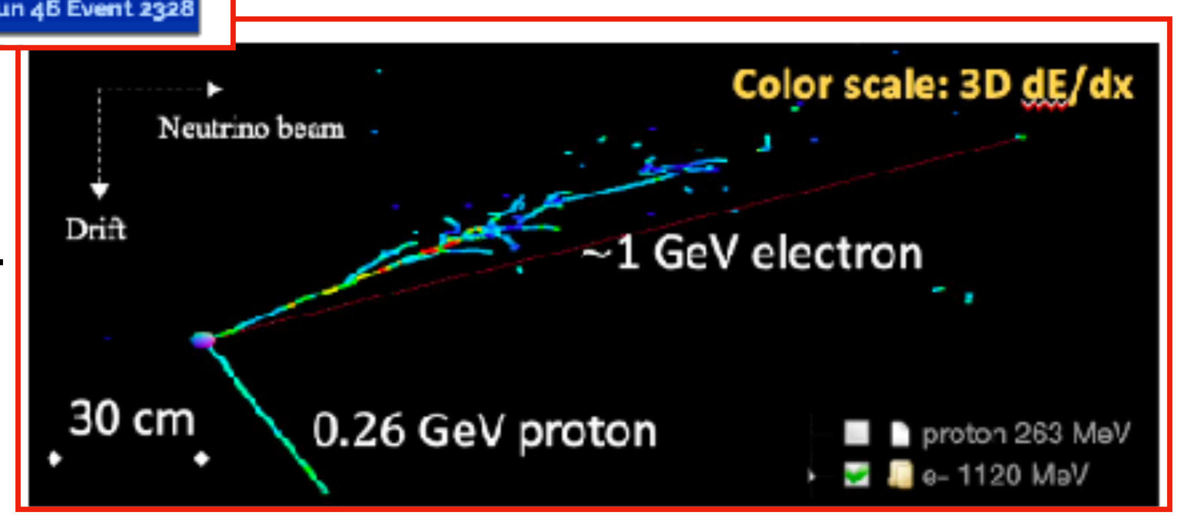
[1e1p CCQE]

[1eX]



Inclusive ν_e scattering.
Wire-Cell Reconstruction.

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



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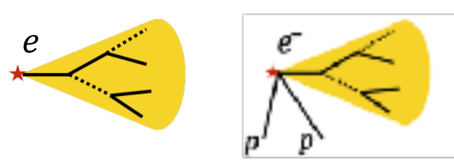
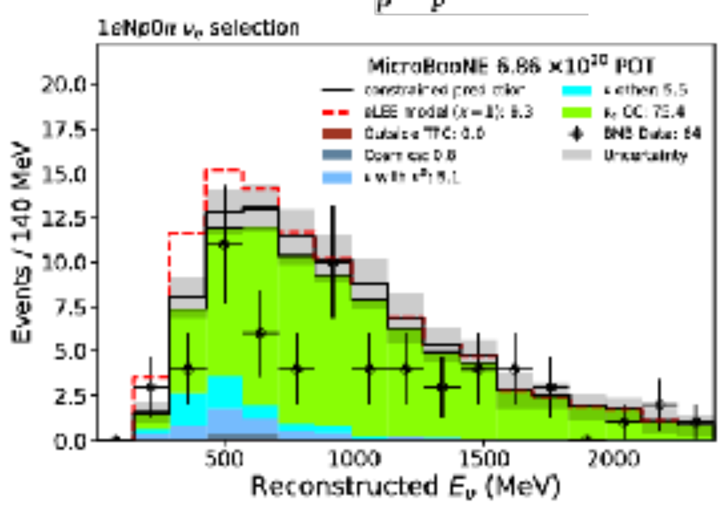
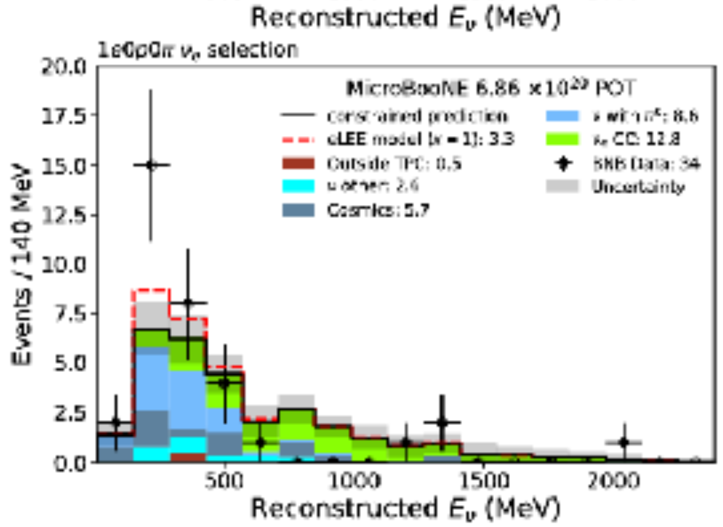
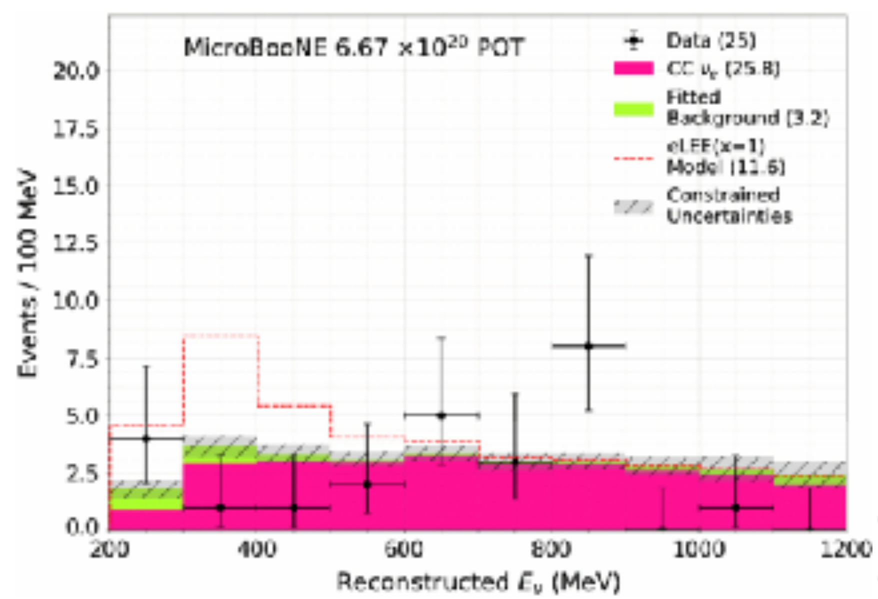
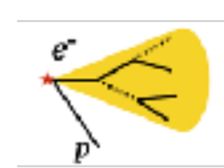
[1eNp0π] and [1e0p0π]





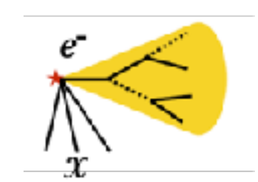


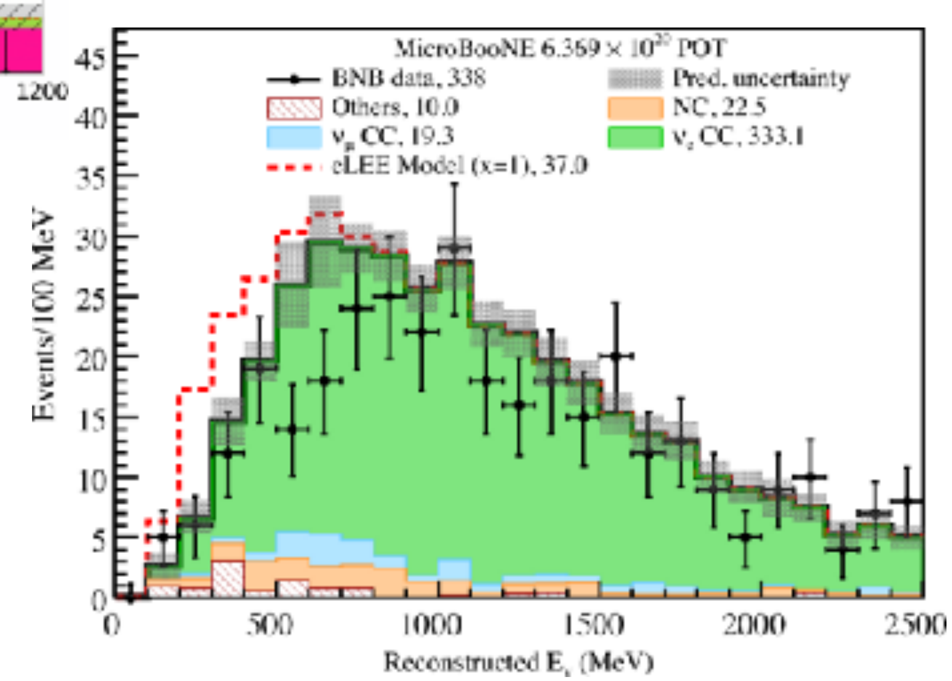




[1e1p CCQE]

[1eX]

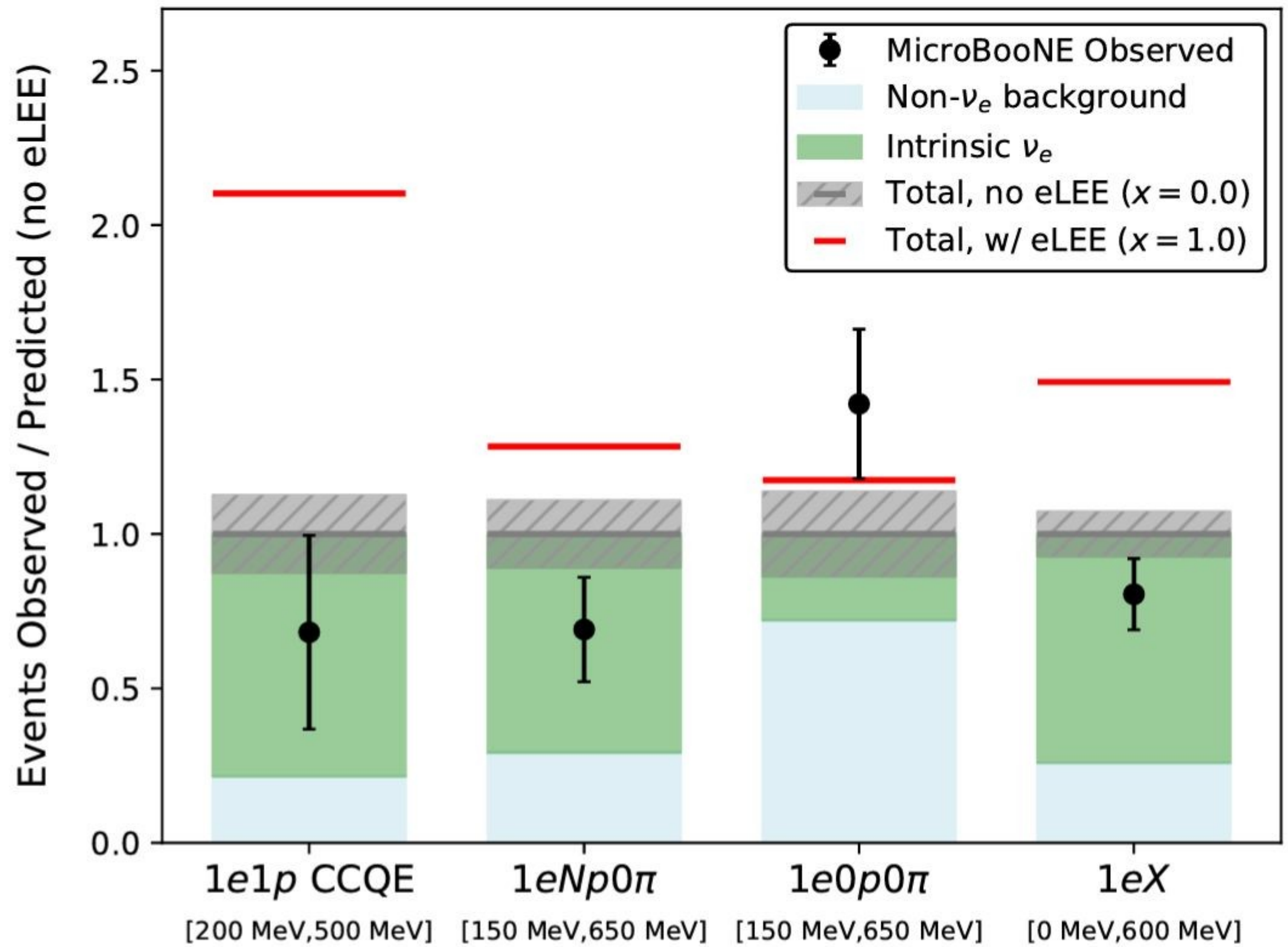




10.1103/PhysRevLett.128.241801

Low-Energy Excess (Electron) Results

- MicroBooNE released results of their first LEE search.
- Observed ν_e rates are statistically consistent with the predicted background rates.
- Rejects electrons as LEE explanation at > 97% CL (inclusive channel)



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First results

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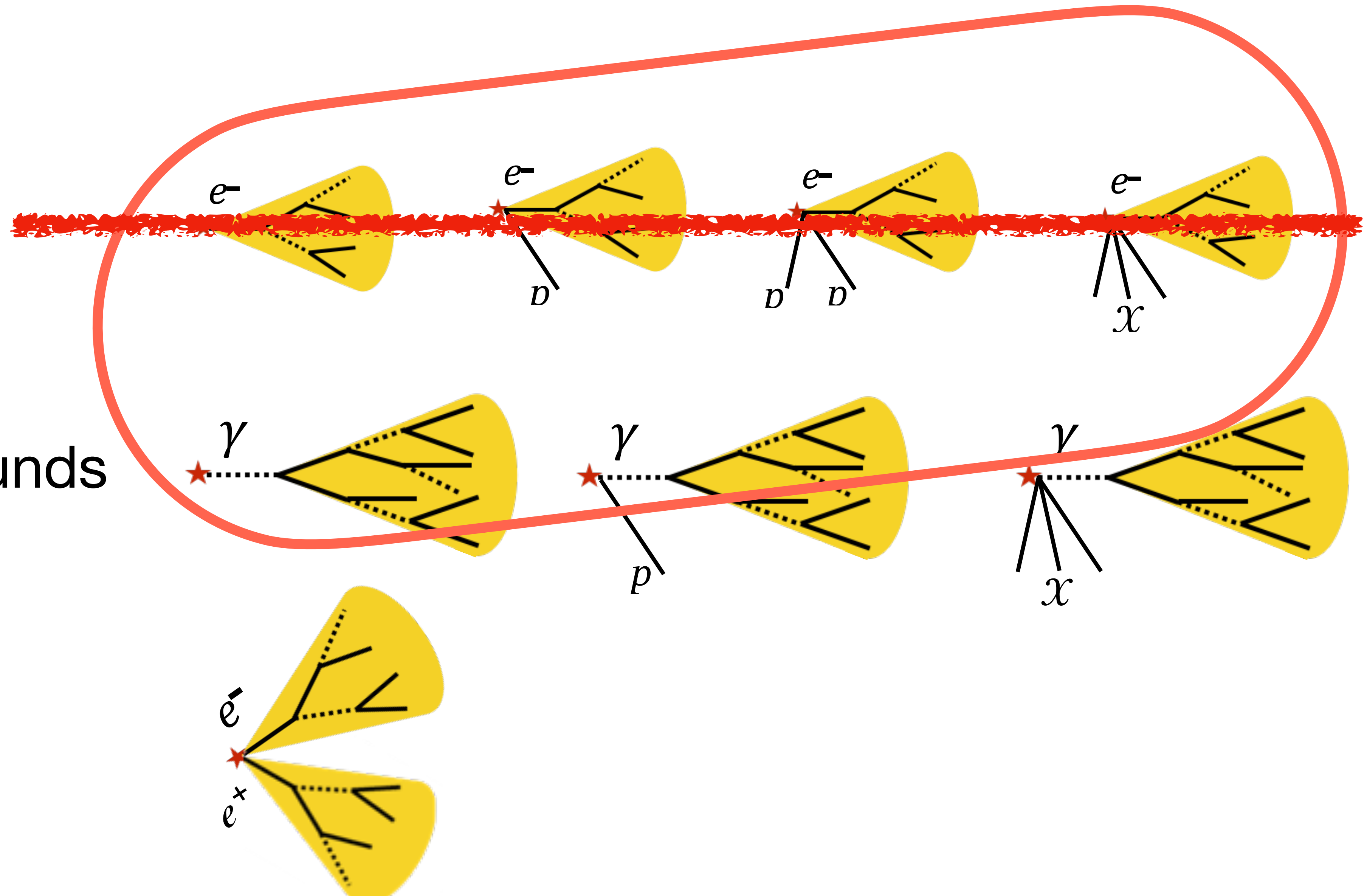
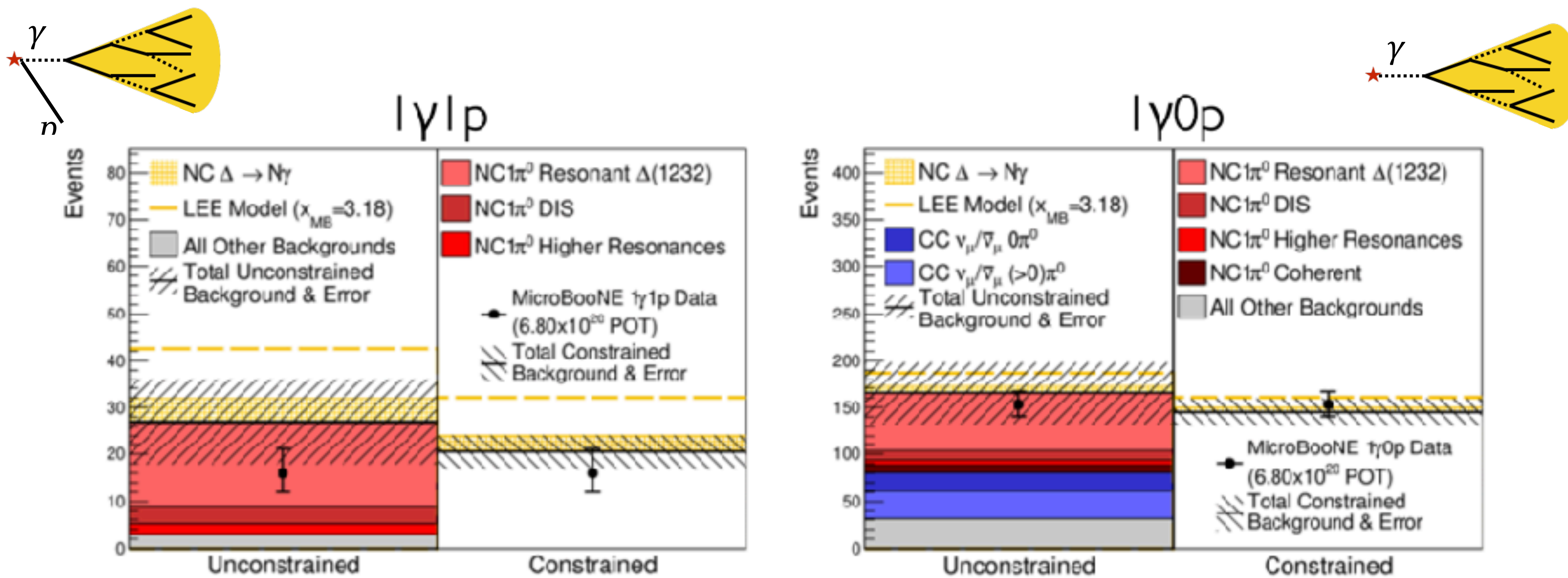
- $e^+ e^-$
  (BSM)



Low-Energy Excess (Photon) Results

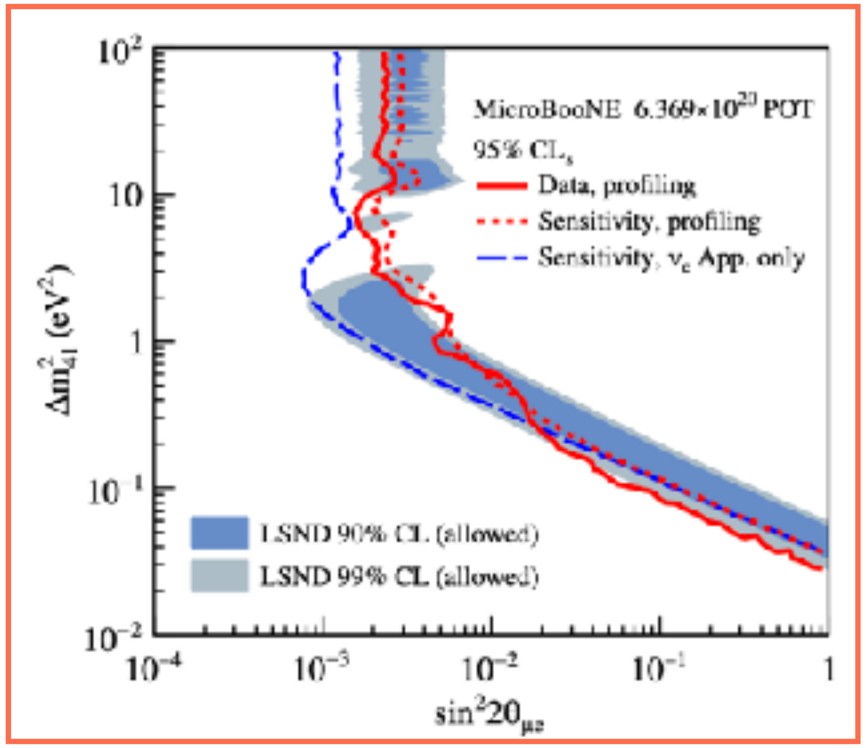
A first search for a photon excess targeted an extremely rare standard model process, Neutral Current **Δ** radiative decay (**Δ**→Nγ).

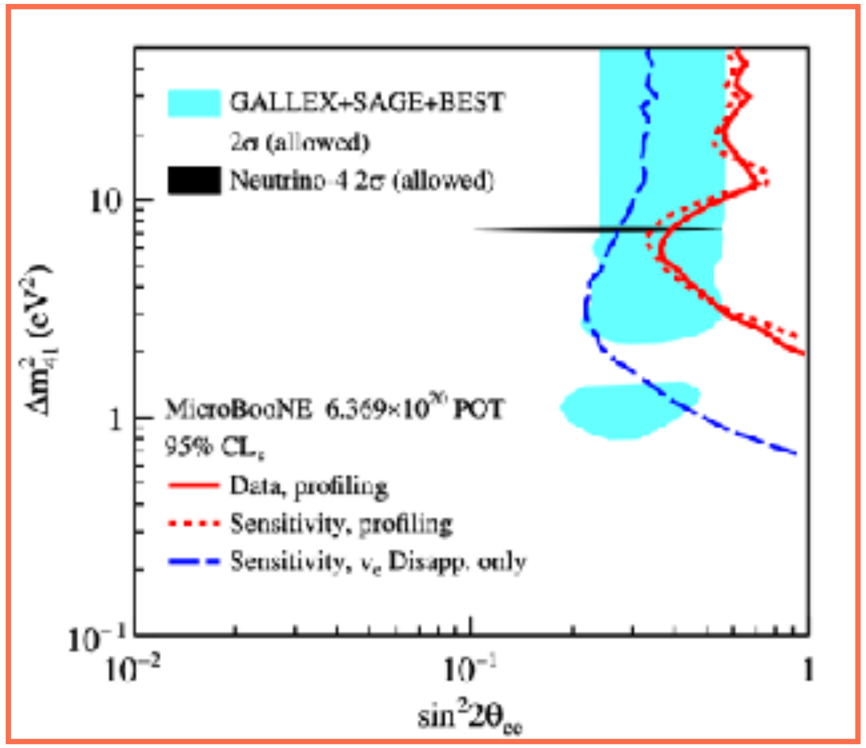


- One single photon search for NC **Δ** → N**γ** (1γ0p, 1γ1p)
- Disfavors NC **Δ**→Nγ backgrounds as a sole source of MiniBooNE's LEE at 94.8% C.L

3+1 Oscillations

- Use the data from the first results (inclusive CC ν_e) to perform a 3+1 sterile neutrino oscillation analysis
- Simultaneously considering appearance and disappearance effects saw no evidence for 3+1 sterile neutrino oscillations
  - For $\nu_\mu \rightarrow \nu_e$, excludes part of the LSND allowed region
  - For $\nu_e \rightarrow \nu_e$, excludes part of the gallium and Neutrino-4 allowed regions





https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.130.011801

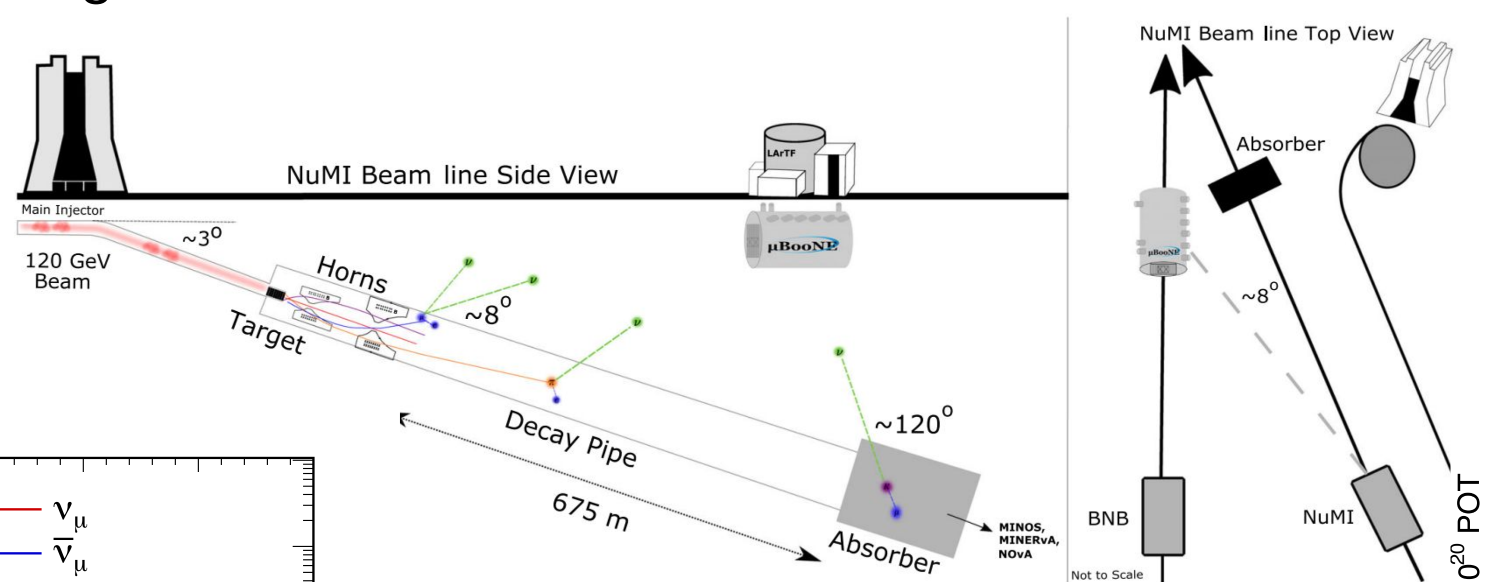
Outline

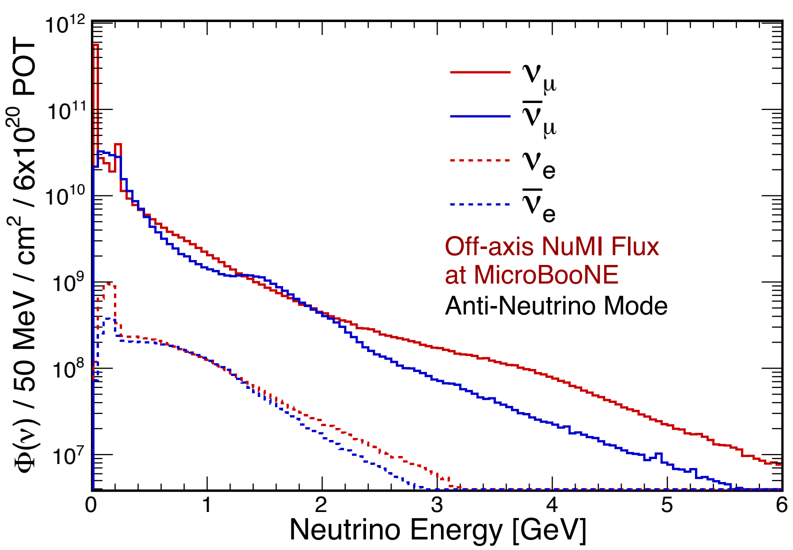
- Short-Baseline neutrino anomalies
- LArTPCs
- The MicroBooNE experiment
  - First results
  - **Ongoing analysis**
- The SBN Program

"The road ahead of MicroBooNE"

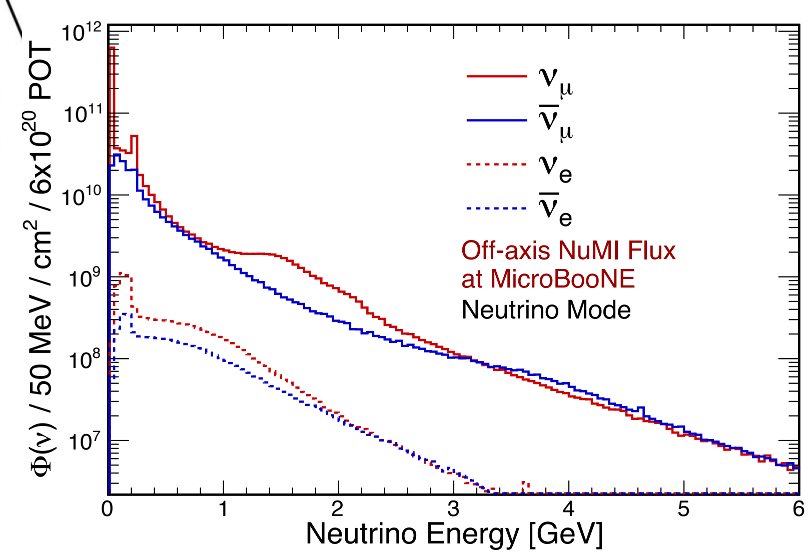
Improving the Sensitivity: BNB+Numi

- Cancellation of ν_e appearance and ν_e disappearance effects leads to degeneracy.
- Different ν_e / ν_μ fluxes ⇒ different appearance/disappearance cancellation
- MicroBooNE can break this degeneracy by using NuMI beam neutrinos reaching the detector at an off-axis angle of 8°



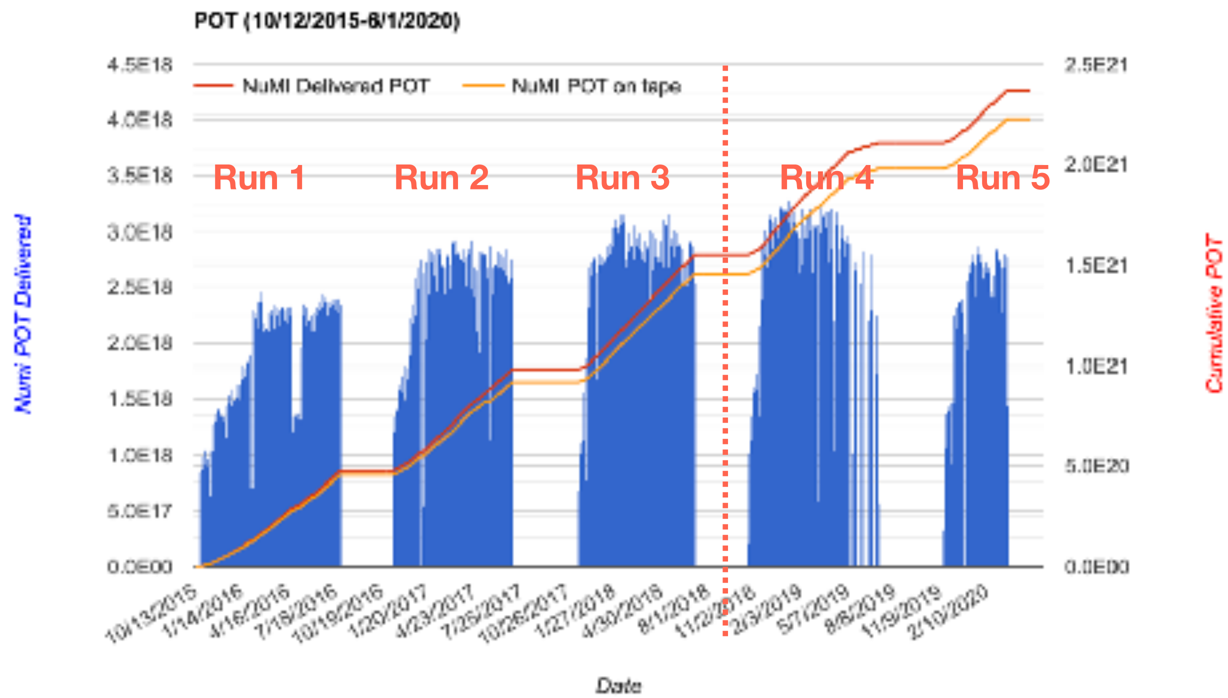


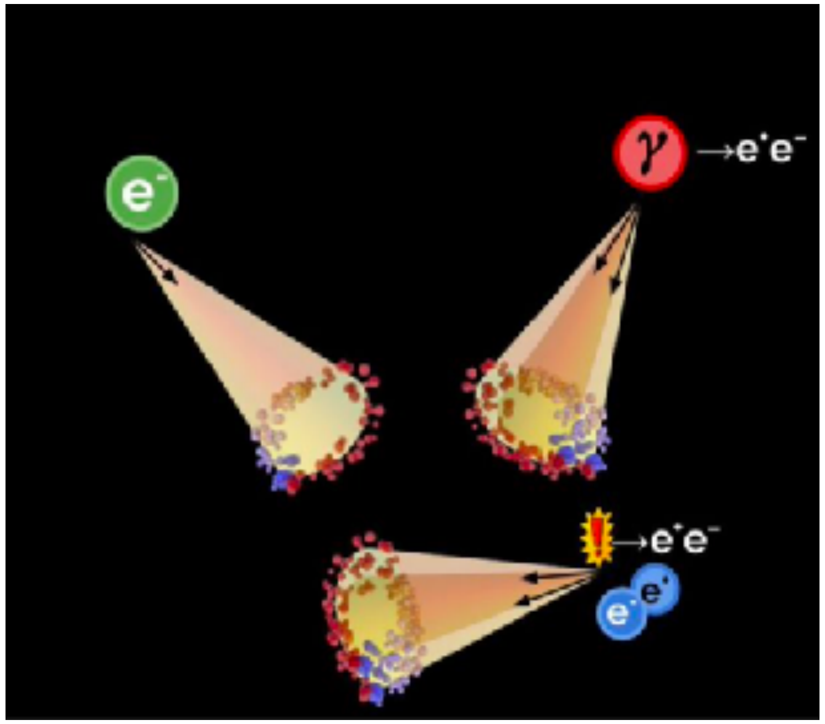
- Intrinsic flux and ν_μ to ν_e ratio in NuMI is quite different from the BNB
- more than doubles statistics



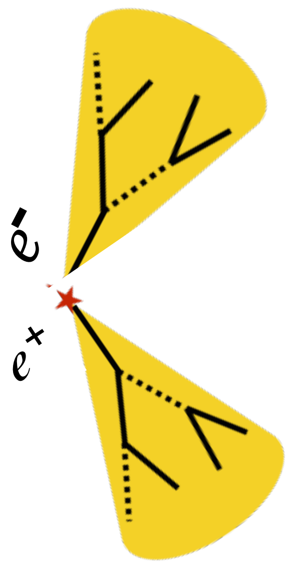
Ongoing analysis

- Run4-5 (including NuMI)
- $e^+ e^-$ as other BSM LEE explanations :
  - Newly proposed BSM scenarios beyond sterile neutrinos
  - Overlapping e+e- final states will mimic a single shower topology
  - Models include dark neutrinos, heavy neutral leptons, new scalars, dark matter, and many more





Cherenkov signal



LArTPC signal

Outline

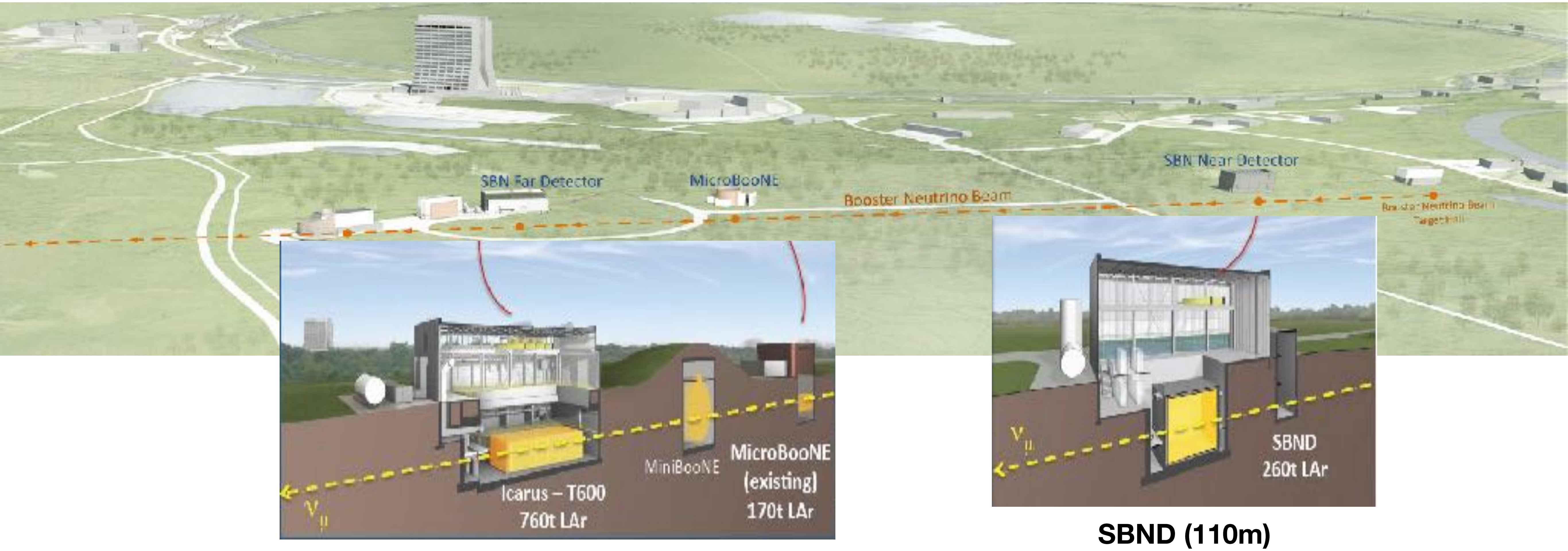
- Short-Baseline neutrino anomalies
- LArTPCs
- The MicroBooNE experiment
  - First results
  - Ongoing analysis
- The SBN Program

Fermilab Wilson Hall

The Short Baseline Neutrino (SBN) program at Fermilab

A multi-detector and multi-beam facility on the Booster Neutrino Beam at Fermilab using the same neutrino beam, nuclear target, detector technology to reduce systematic uncertainties.

- Neutrino beam from pion decay-in-flight mostly. Well-known beam, same as MiniBooNE (PRD 79, 072002).
- 3 Liquid Argon Time Projection Chamber (LArTPC) detectors.



ICARUS (600m)
taking data

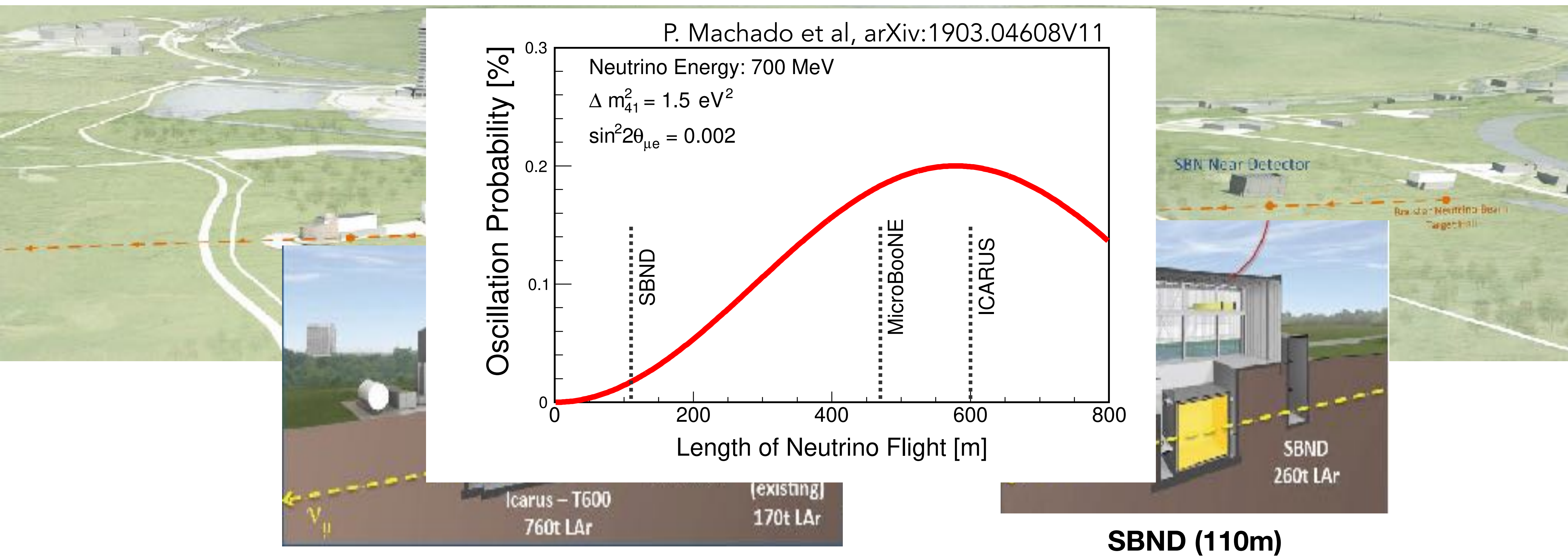
MicroBooNE (470m)
finished taking data 2021

SBND (110m)
under construction

M.Nebot-Guinot

The Short Baseline Neutrino (SBN) program at Fermilab

- Resolve the question of the existence of sterile neutrinos.

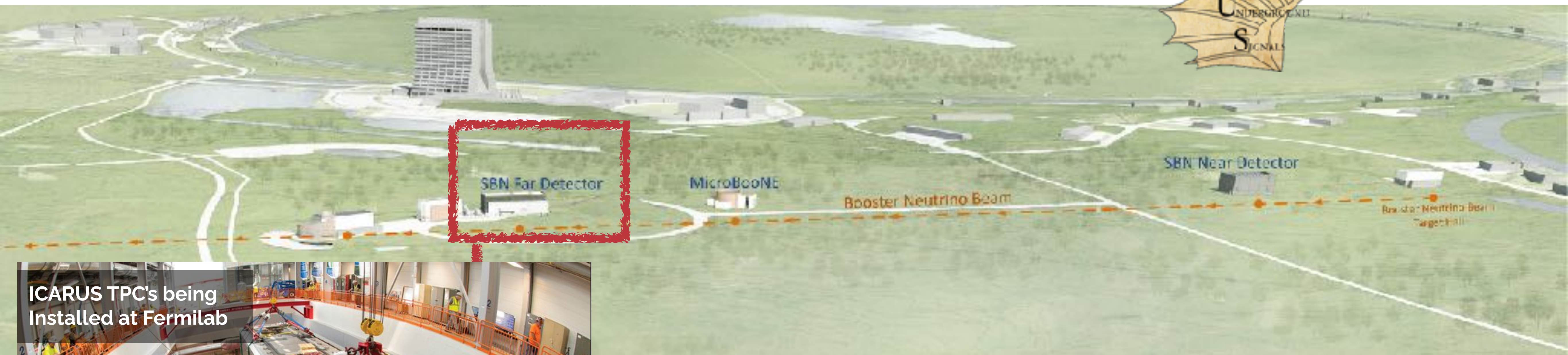


ICARUS (600m)
taking data

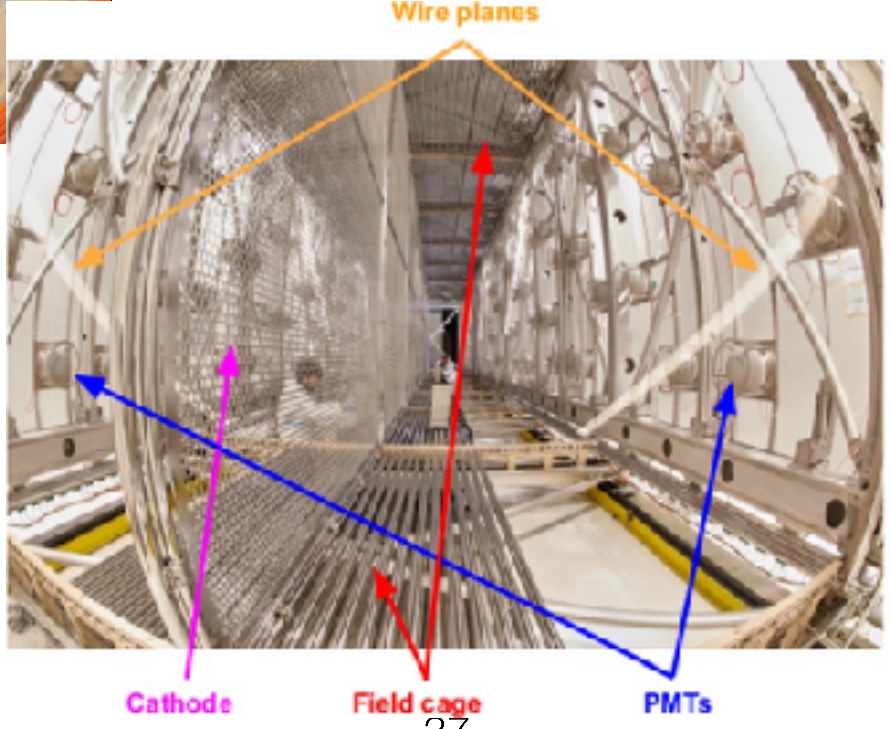
MicroBooNE (470m)
finished taking data 2021

SBND (110m)
under construction

The SBN Far Detector



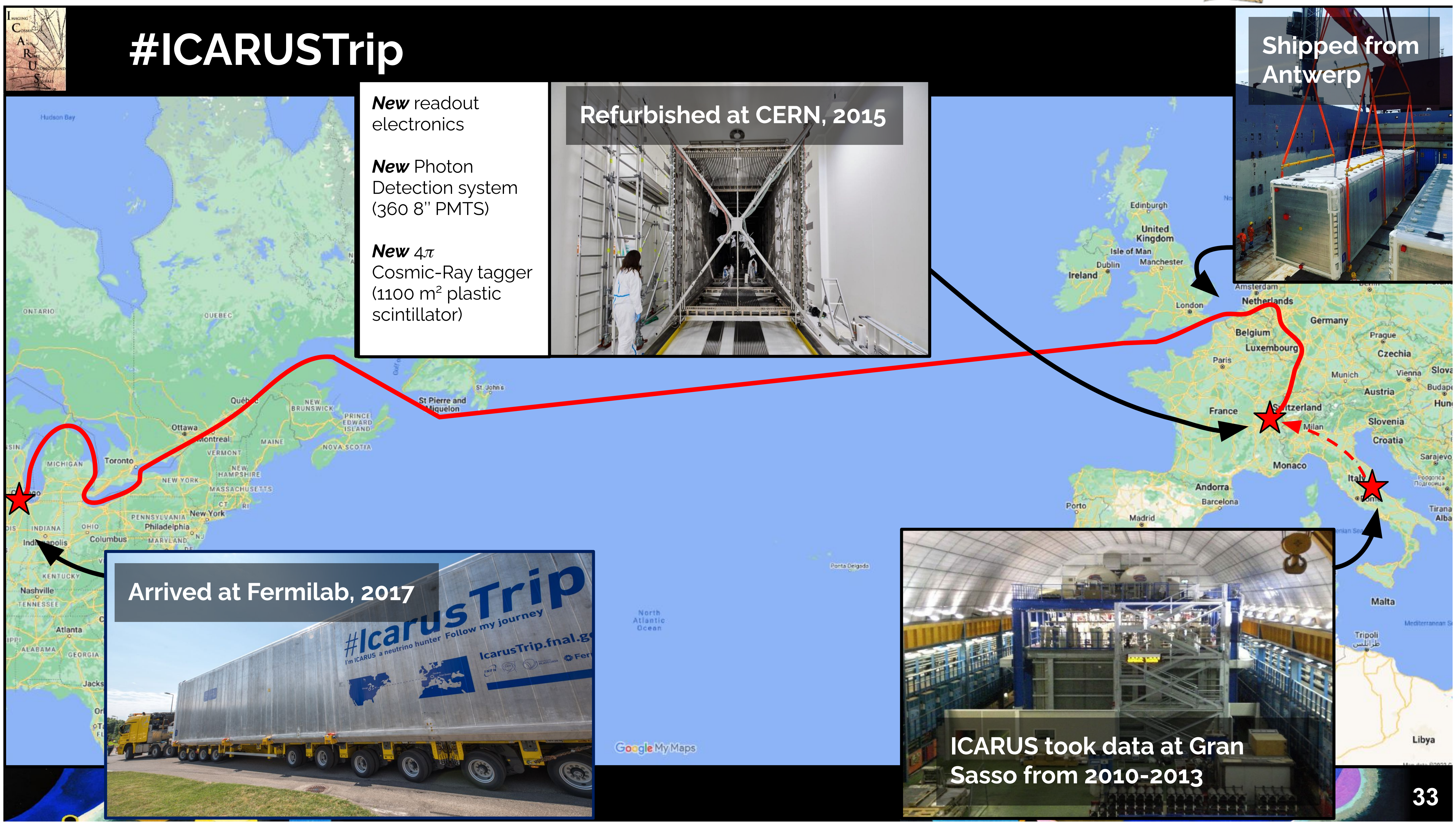
ICARUS at 600m from the BNB target, is the **far-detector of the SBN program**, close to the oscillation maximum for O(1 eV^2) sterile neutrinos and has an **active volume over five times that of MicroBooNE!**



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

M.Nebot-Guinot

The SBN Far Detector



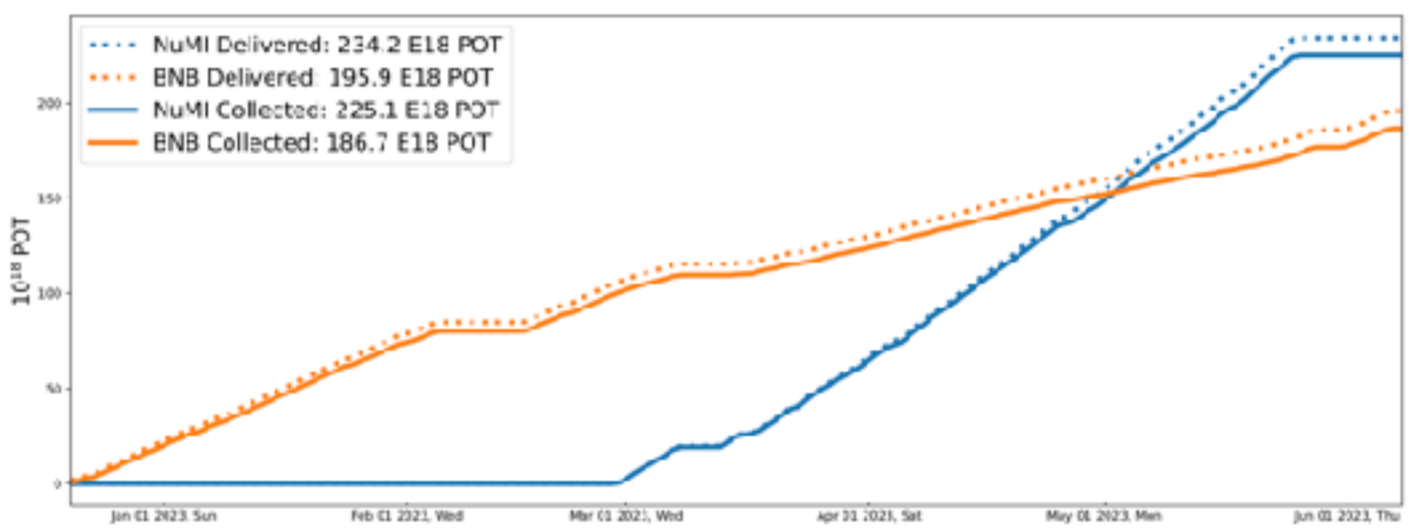
The ICARUS detector was the first large scale demonstration of LArTPC technology for neutrino physics, when it ran for 3 years (2010-2013) at Gran Sasso in Italy, using the CERN Neutrino to Gran Sasso (CNGS) beam.

M.Nebot-Guinot

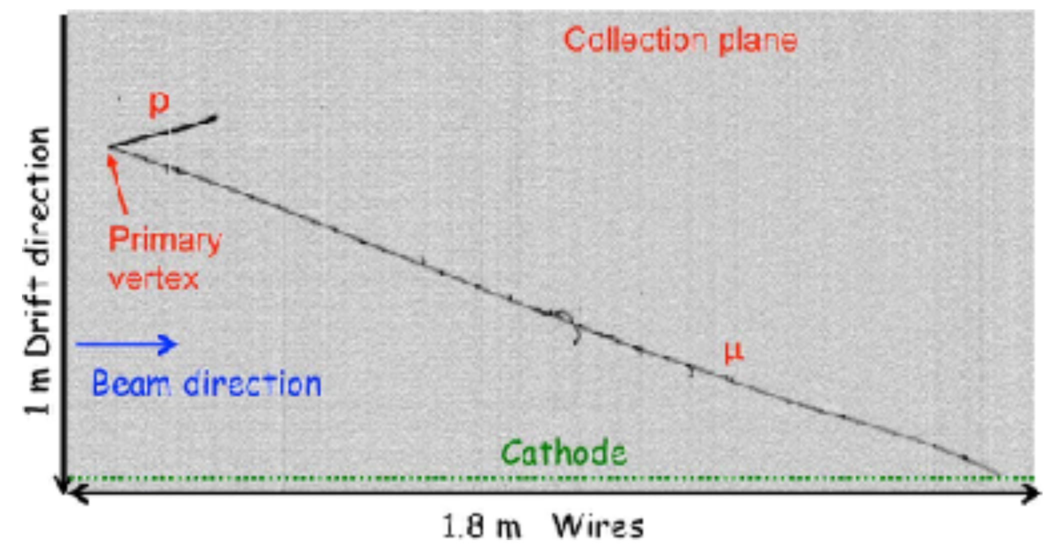
Status

- Started data taking on June 2022
- DAQ efficiency > 95%
- Trigger based on coincidence of PMTs and beam spill

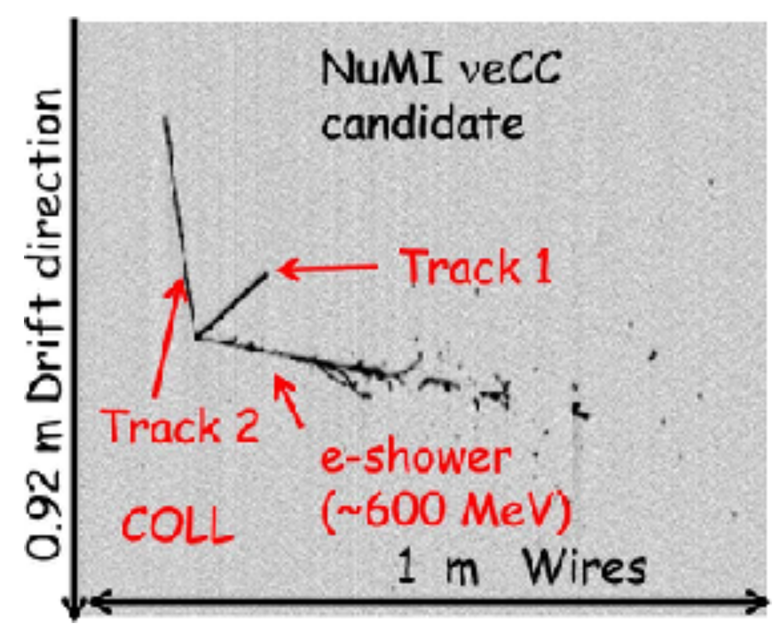
Run 2:



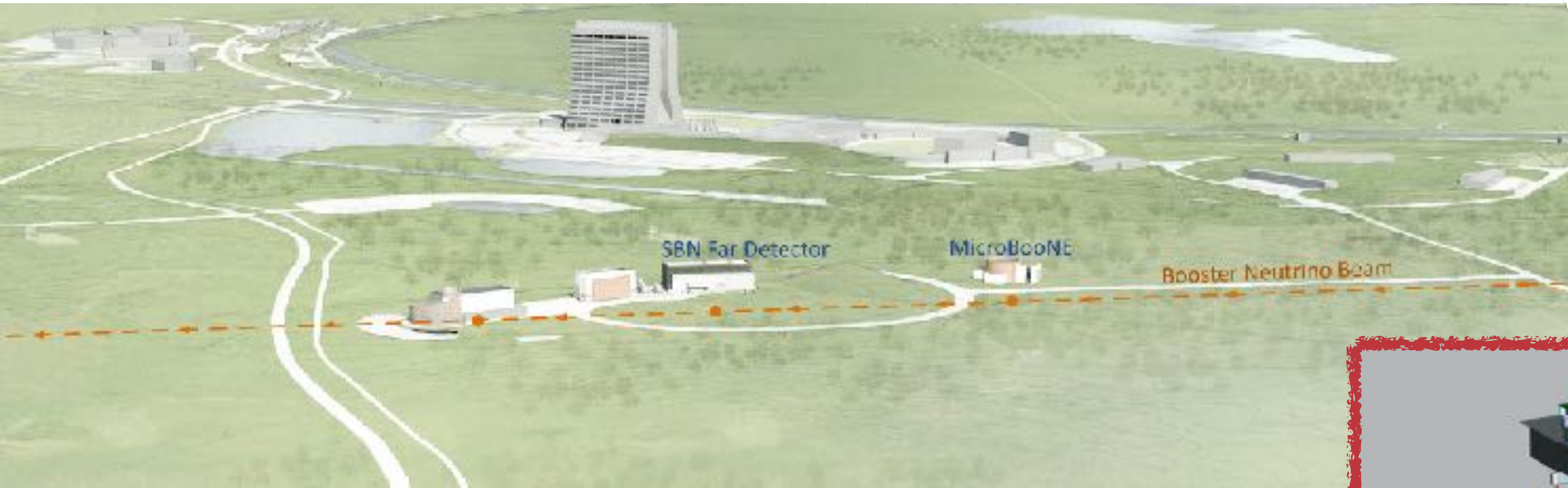
	Run1 (POT):	Run2 (POT):
	Jun 9 – Jul 10, 2022	Dec 2022 – present
BNB	4.1×10^{19}	1.9×10^{20}
NuMI	6.8×10^{19}	2.2×10^{20}

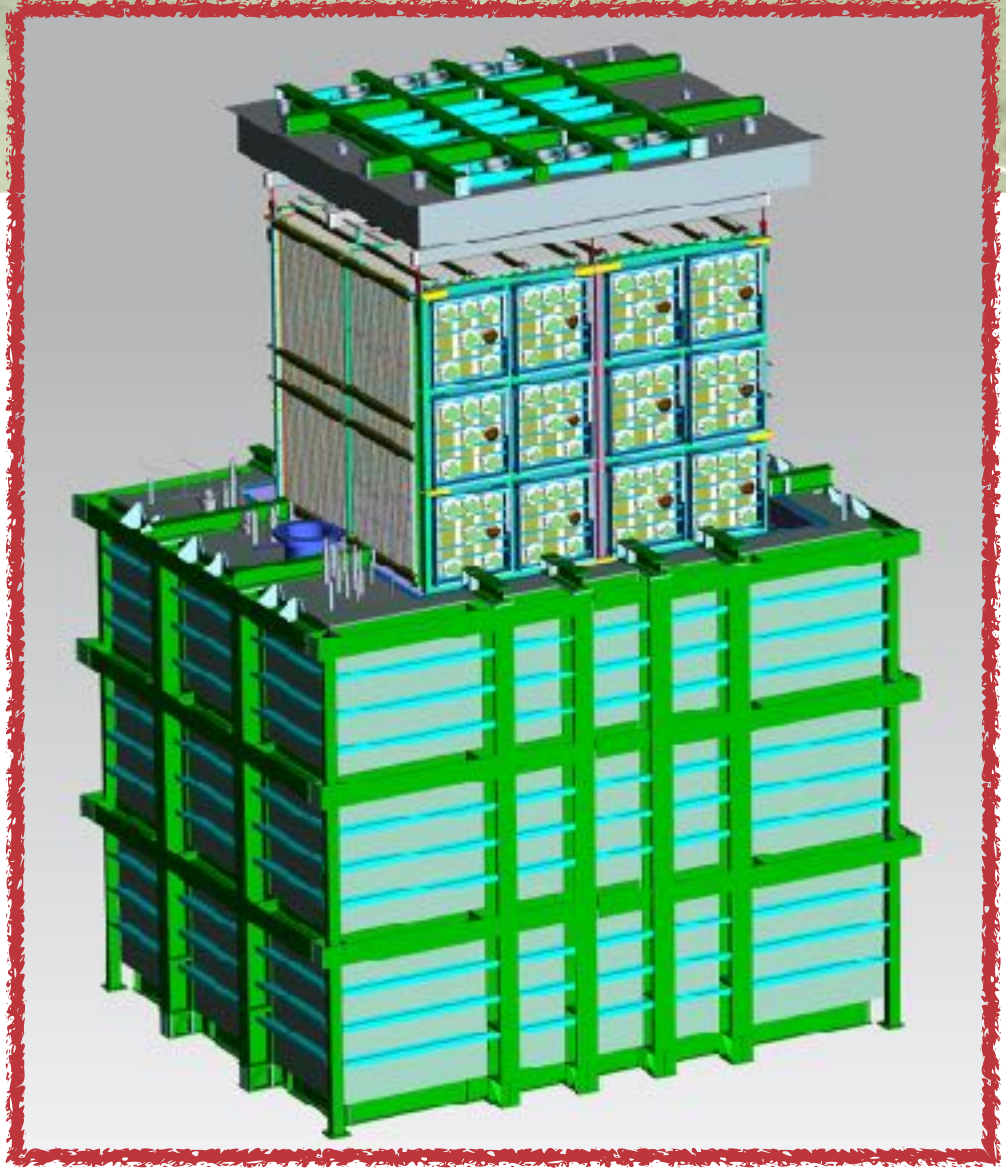


Eur. Phys. J. C 83, 467 (2023)

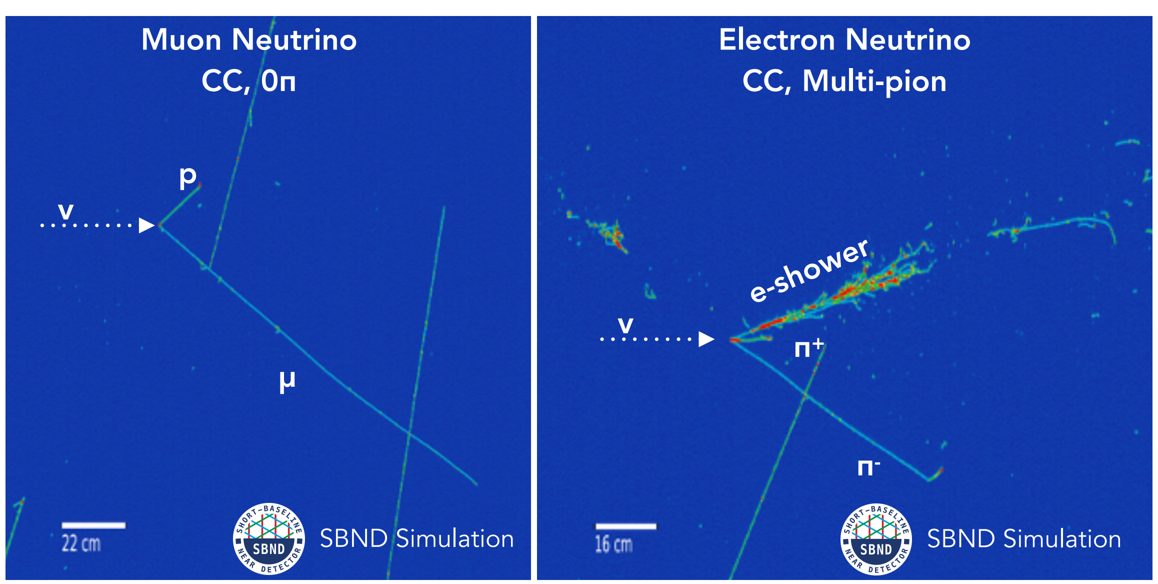


The SBN Near Detector





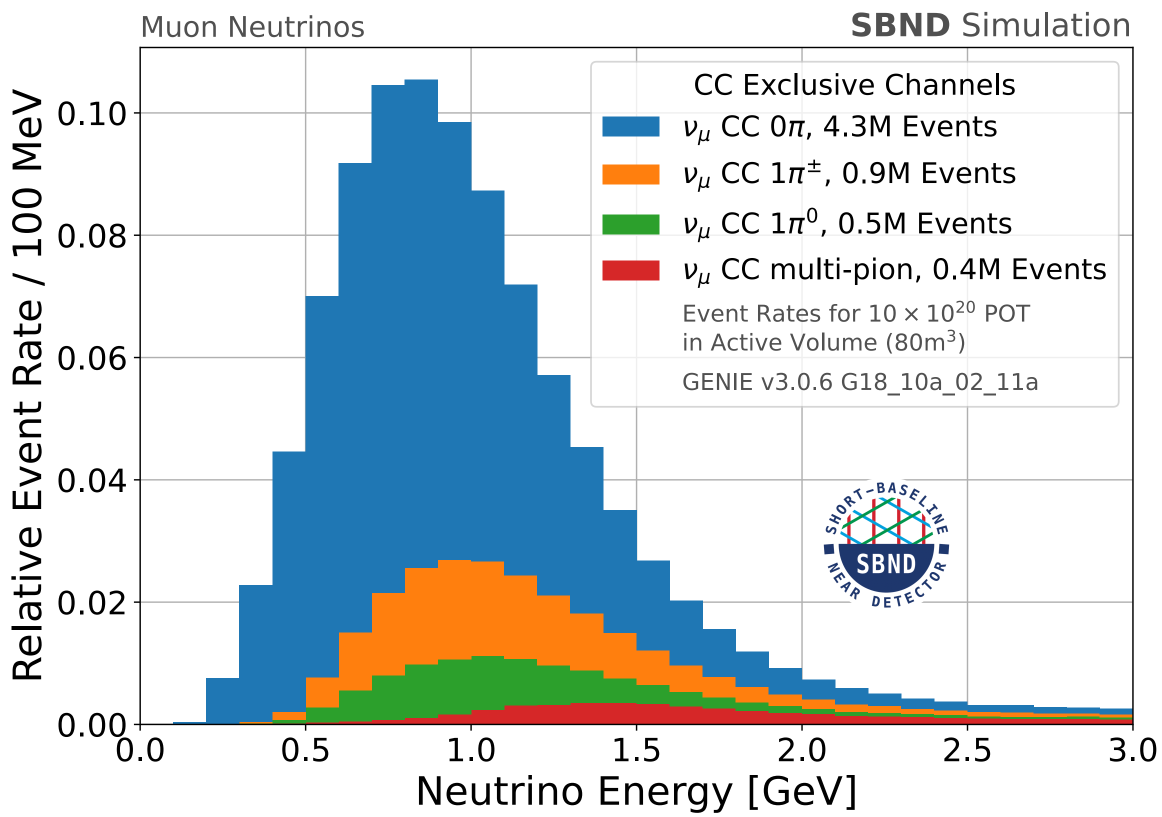
Short-Baseline Near Detector (SBND) is located just 110 meters from the Booster Neutrino Beam target, and has 112 tons of liquid argon within the active volume of its detection systems.



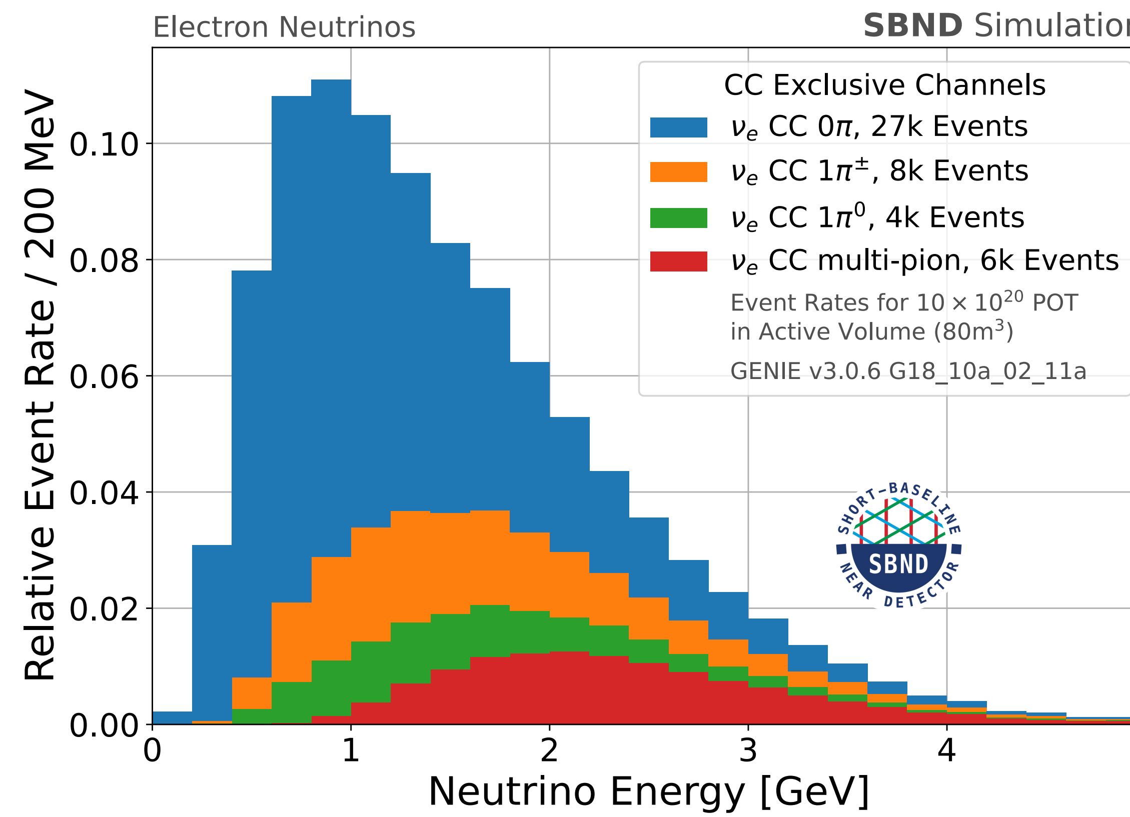
The SBN Near Detector

SBND physics goals

The near detector plays a fundamental role on answering whether the MiniBooNE low energy excess is intrinsic to the BNB or if it appears along the beam-line.



1.5M ν_μ CC events in 1 year



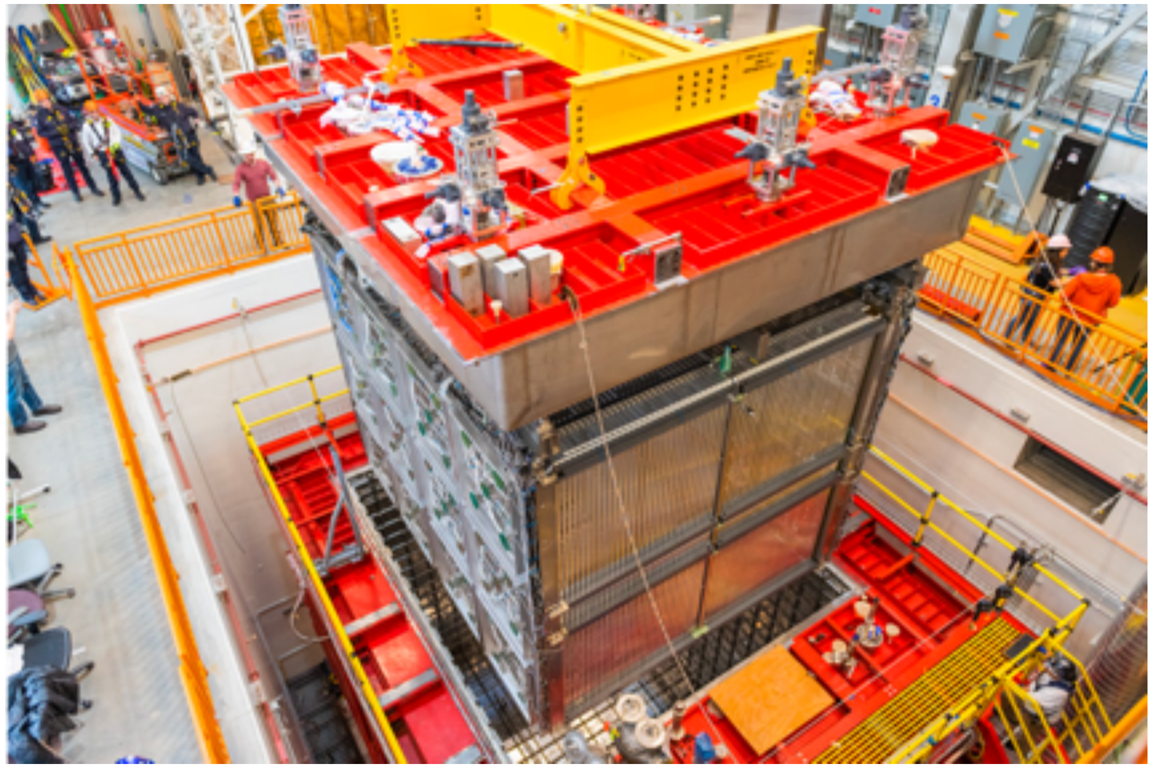
12k ν_e CC events in 1 year

- Constrain the un-oscillated flux for sterile neutrino searches.
- Collect the largest sample of neutrino-argon interactions to date.

SBND will observe 5000 ν-events/day!

Status

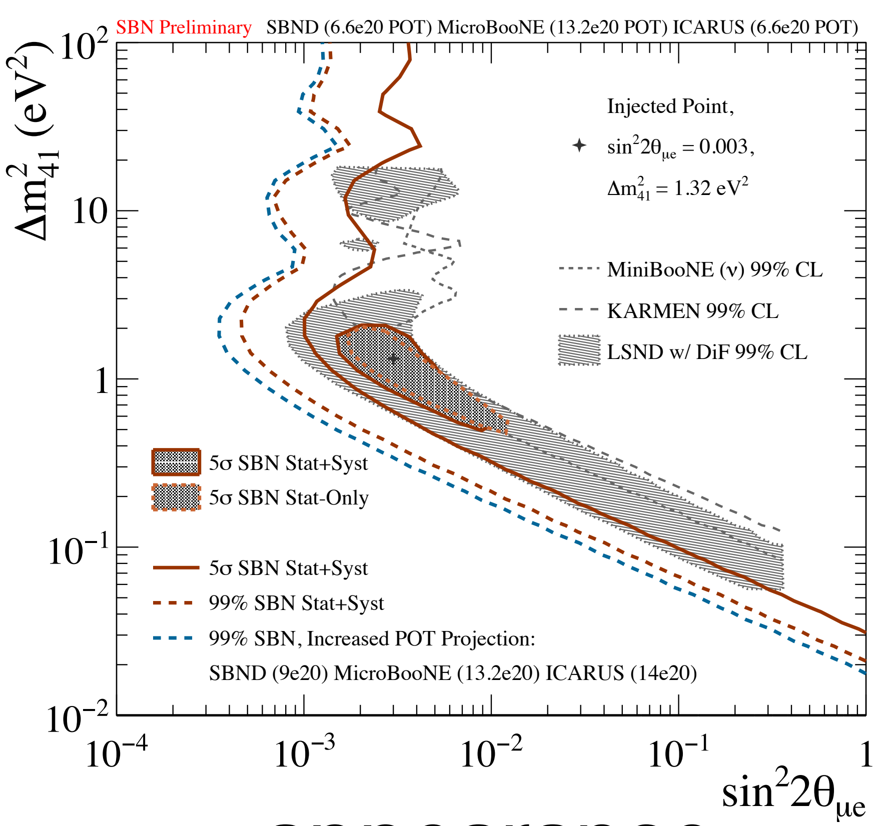
- Detector installed in the cryostat
- Almost ready for (cryo) commissioning



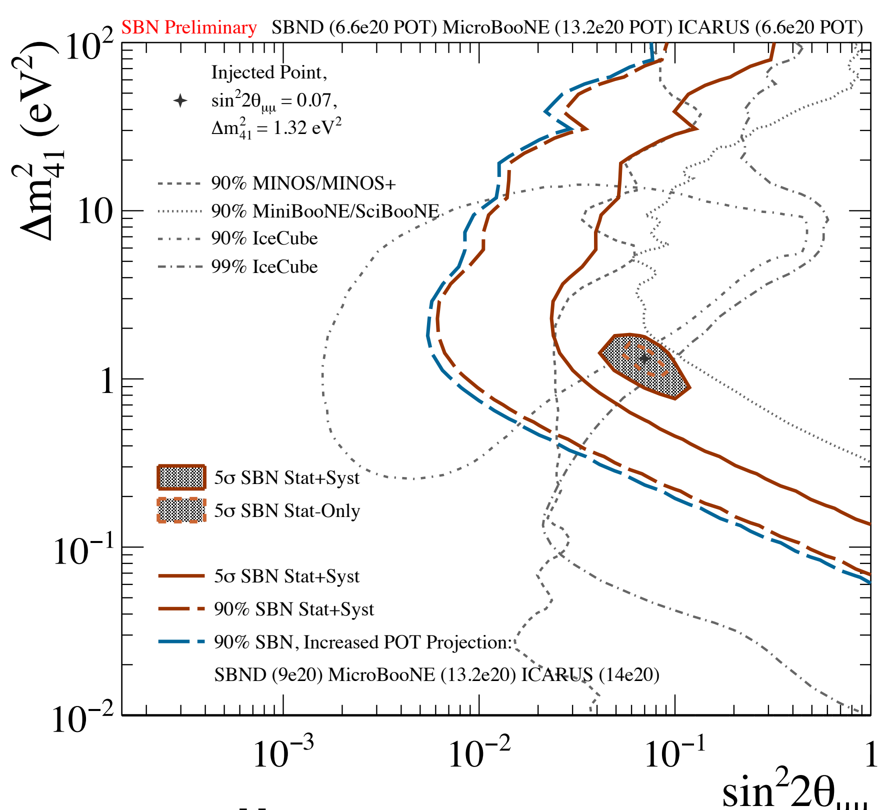
SBN LEE search

SBN sterile neutrino oscillation sensitivity

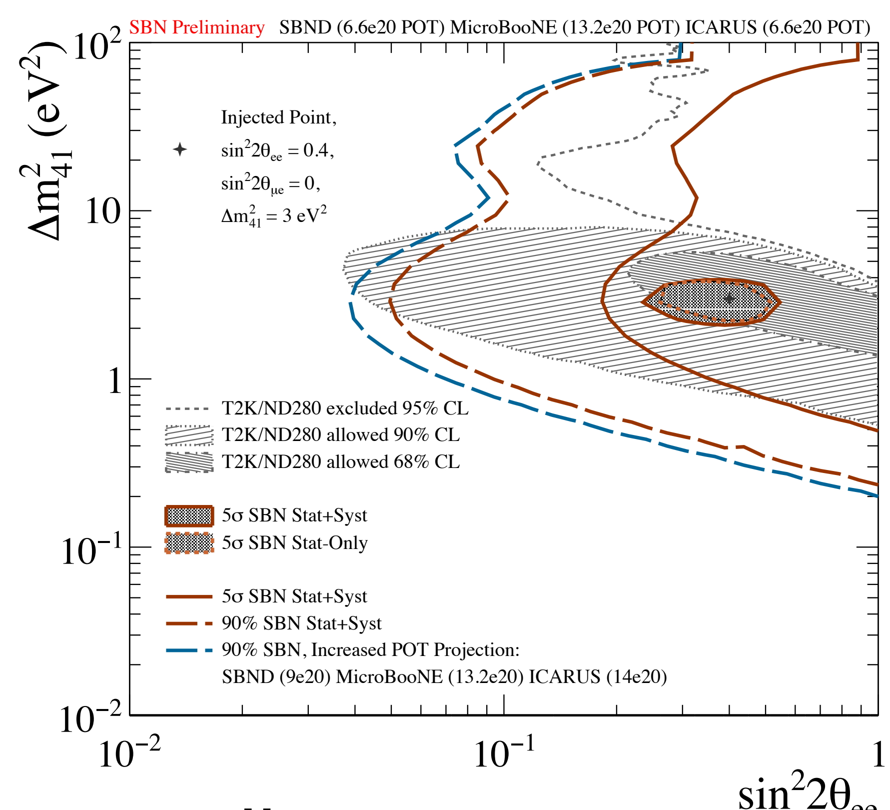
- SBN sensitivities for 6.6 e20 protons on the **BNB** target (MicroBooNE at 13.2e20) as per SBN proposal.
- SBND will see over 35,000 intrinsic ν_e in 6.6 e20 POT. Allows for a direct accelerator based ν_e disappearance search, complementary to other ν_e disappearance (reactor and radioactive source) experiments



ν_e appearance



ν_μ disappearance



ν_e disappearance

ICARUS will leverage its position ~5.7⁰ off axis in the **NuMI** beam to perform a ν_e disappearance

Summary

- The MicroBooNE experiment was designed to test the nature of the excess of single electromagnetic shower events seen by MiniBooNE
- MicroBooNE results with half of its data
  - Reject the simple ν_e model as the MiniBooNE low energy excess at >97%
  - Disfavor NC $\Delta \rightarrow N\gamma$ as the MiniBooNE low energy excess
  - No evidence of sterile neutrino oscillation
- Plan to improve this results in the near future with the inclusion of data from the NuMI and run 4-5, and new MicroBooNE LEE analyses, including searches for new models and more general event topologies
- SBN program is expected to provide important interpretation of oscillation of eV-scale neutrino
- Unique features LArTPCs offer a number of ν-Ar cross section measurements and BSM searches

LEE + Cross sections, BSM and R&D

MicroBooNE Papers

2017 2018 2019 2020 2021 2022 2023

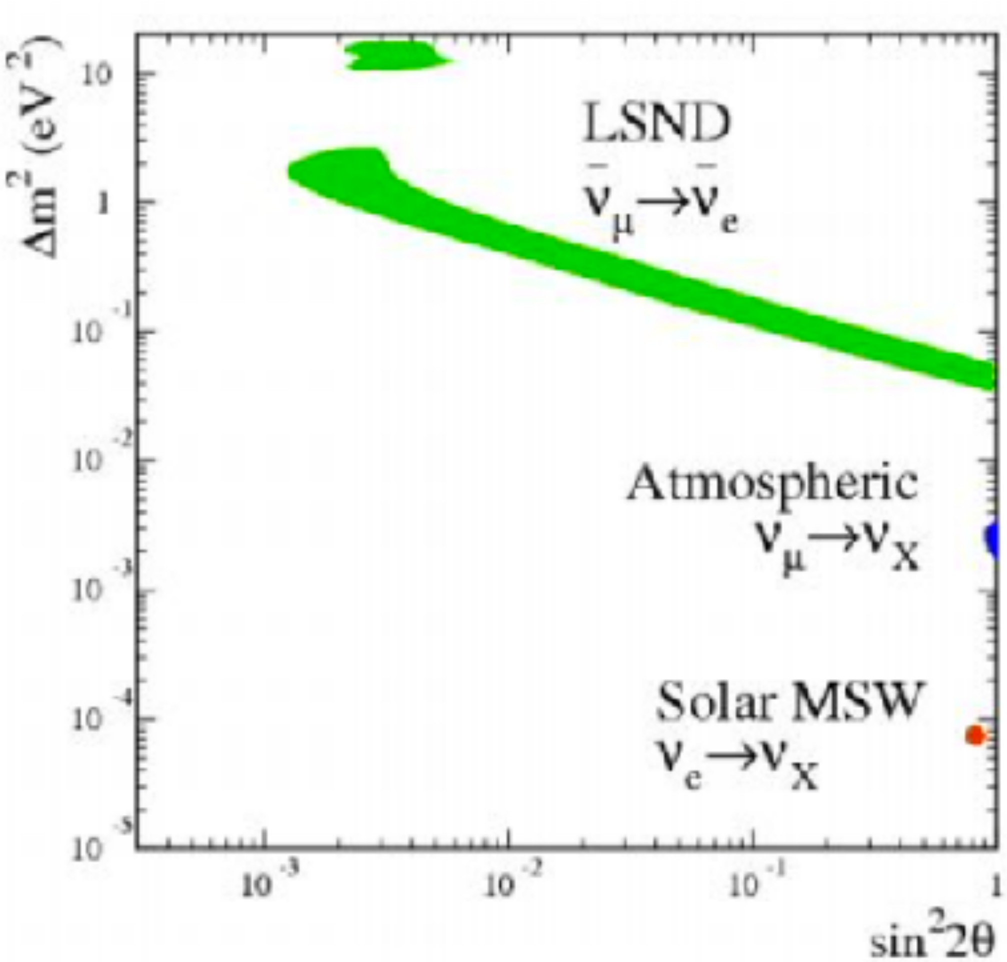
56 papers

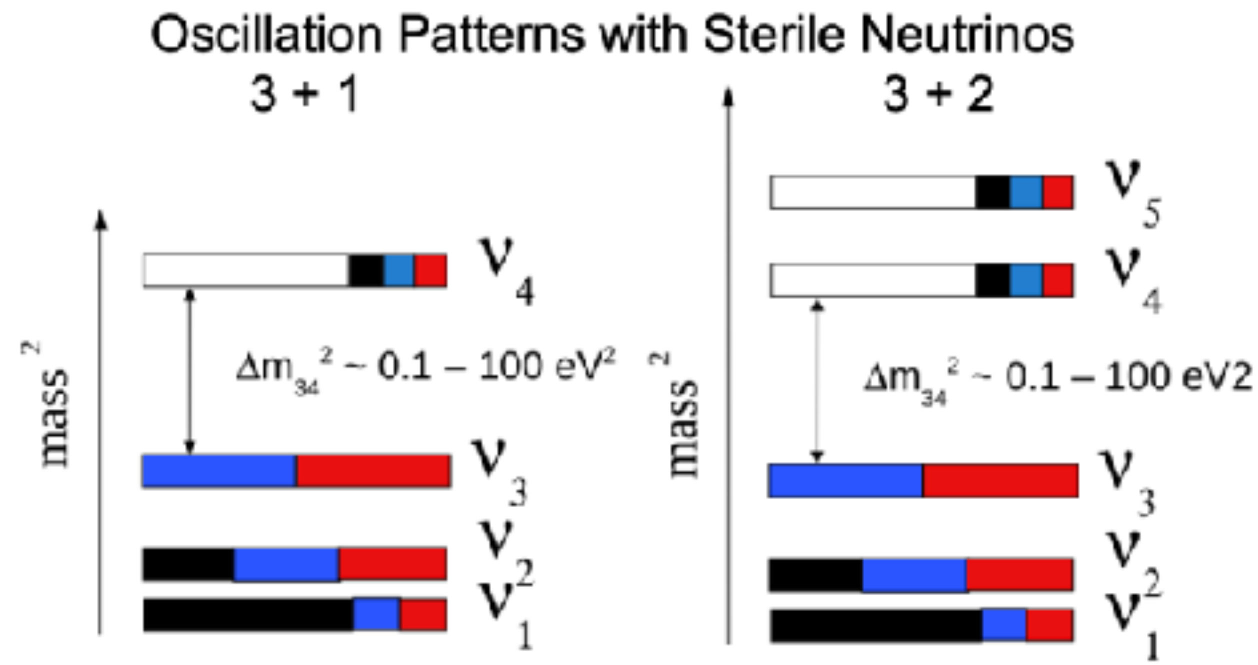
First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber
Multi-differential cross section measurements of muon-neutrino-argon quasielastic-like reactions with the MicroBooNE detector
First double-differential measurement of kinematic imbalance in neutrino interactions with the MicroBooNE detector
First measurement of quasi-elastic Λ baryon production in muon antineutrino interactions in the MicroBooNE detector
First measurement of differential cross sections for muon neutrino charged current interactions on argon with a two-proton final state in the MicroBooNE detector
First constraints on light sterile neutrino oscillations from combined appearance and disappearance searches with the MicroBooNE detector
Differential cross section measurements of charged current ν_e interactions without final-state pions in MicroBooNE
Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector
Measurement of neutral current single π^0 production on argon with the MicroBooNE detector
Observation of radon mitigation 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
Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data
Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
Search for heavy neutral leptons decaying into muon-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
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector
Design and Construction of the MicroBooNE Cosmic Ray Tagger System
Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
Design and Construction of the MicroBooNE Detector

Thanks on behalf of the MicroBooNE Collaboration

Backup

LSND

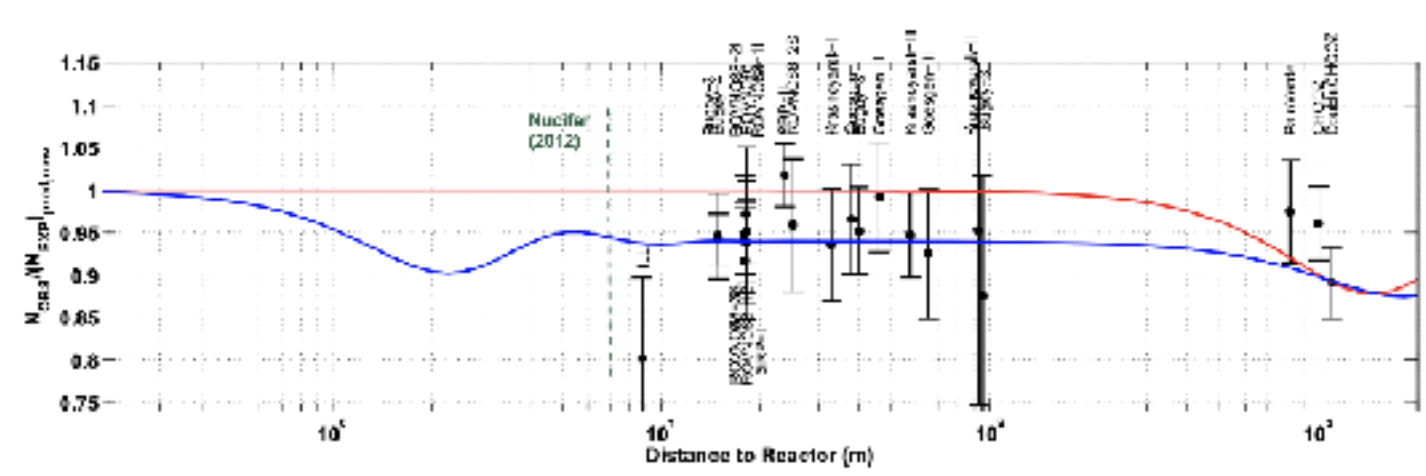

LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Atmospheric
$\nu_\mu \rightarrow \nu_X$
Solar MSW
$\nu_e \rightarrow \nu_X$
Δm^2 (eV^2)
$\sin^2 2\theta$


Oscillation Patterns with Sterile Neutrinos
3 + 1
3 + 2
mass^2
Δm_{34}^2 ~ 0.1 – 100 eV^2
Δm_{34}^2 ~ 0.1 – 100 eV2
ν_5
ν_4
ν_3
ν_2
ν_1

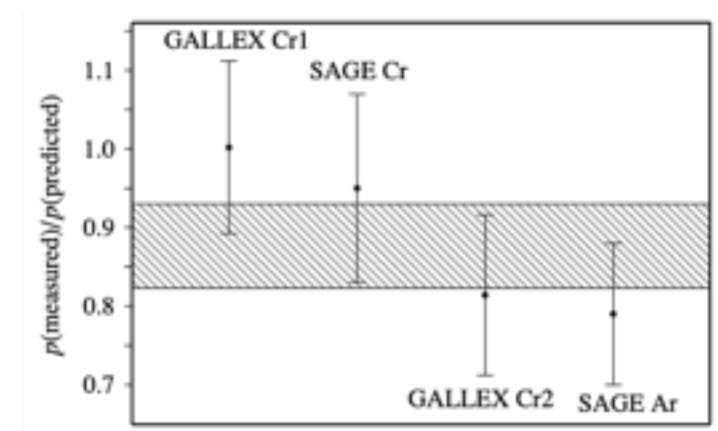
Sterile neutrino scenario

- MiniBooNE low energy excess
- Anomalies from Gallium and reactor experiments
- Existence of sterile neutrinos?
- Doesn't fit into the SM
- Tension between experiments

Observed in neutrino experiments in the last 20 years:
Deficit of anti-ν_e detected from nuclear reactors (reactor anomaly).
Deficit of ν_e from intense calibration sources in solar ν experiments (gallium anomaly).



- Resolve the nature of the MiniBooNE like signal.



Flux refinement for Reactors: Phys.Letters B Volume 829, (2022) 10
BEST experiment on Gallium: Phys.Rev.D 105 (2022) 5, L051703

Experiment	Type	Channel	Significance
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ
LSND	DAR accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$	4.8 σ

Titl

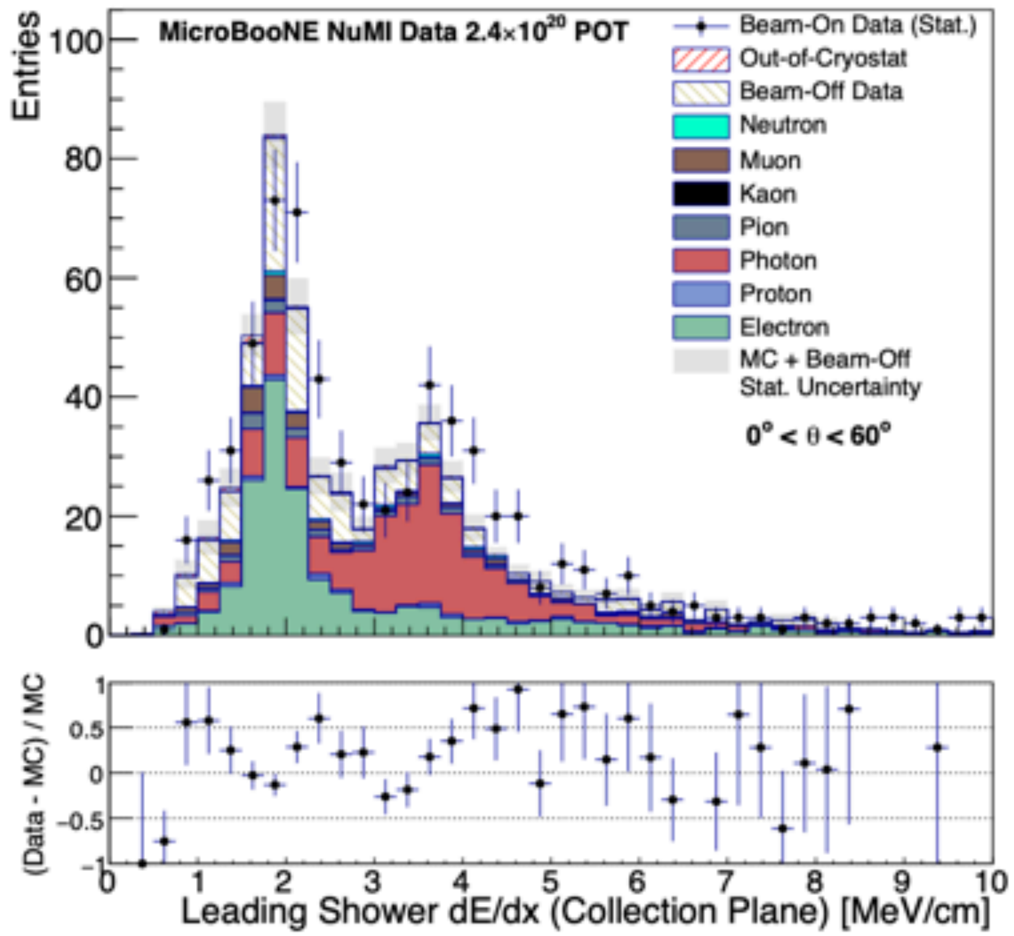
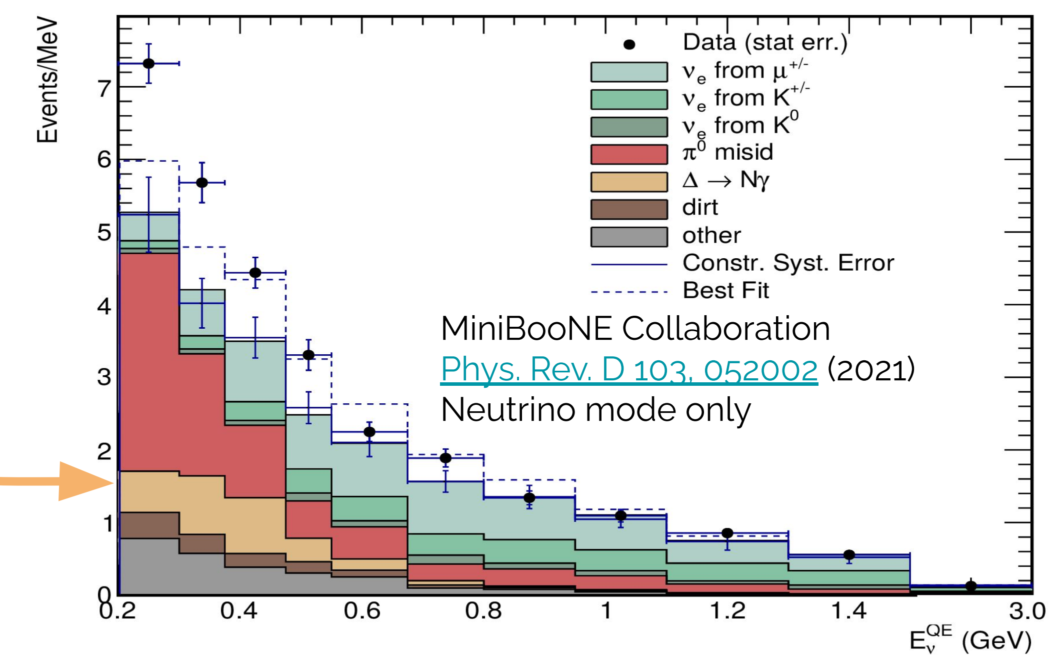


Figure 7.4: The dE/dx for selected electron neutrino shower candidates using data from the MicroBooNE experiment. This distribution is limited to shower angles ranging from $0^\circ < \theta < 60^\circ$ (forward-going) to mitigate the effects of induced charge on neighbouring wires that is not included in the simulation. The peak in the single MIP region (∼2 MeV/cm) is dominated by electrons (green) while the peak in the double MIP region (∼4 MeV/cm) is dominated by photons (red). This separation allows the discrimination of electron and photon induced EM showers [5].

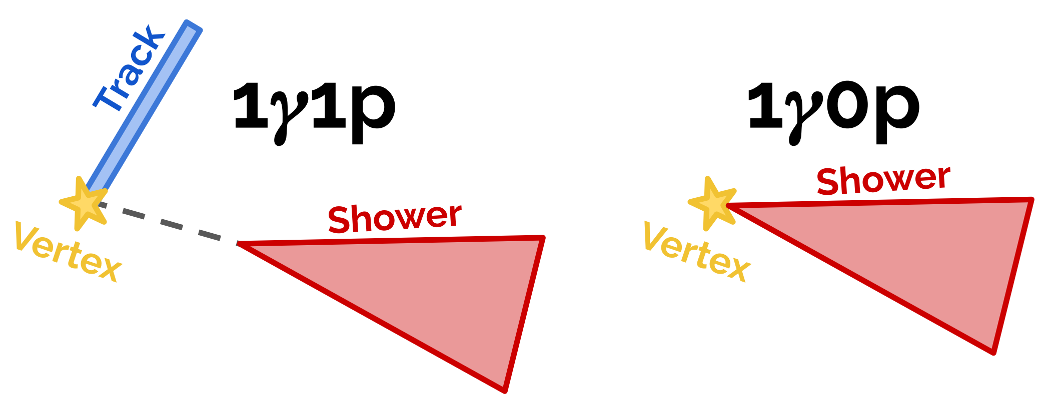
MicroBooNE's First Low-Energy Excess (Photon) Results

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:



The nucleus is a complex system…

Signal-Background Migration

The nucleon is not at rest!
Fermi Motion must be modeled.

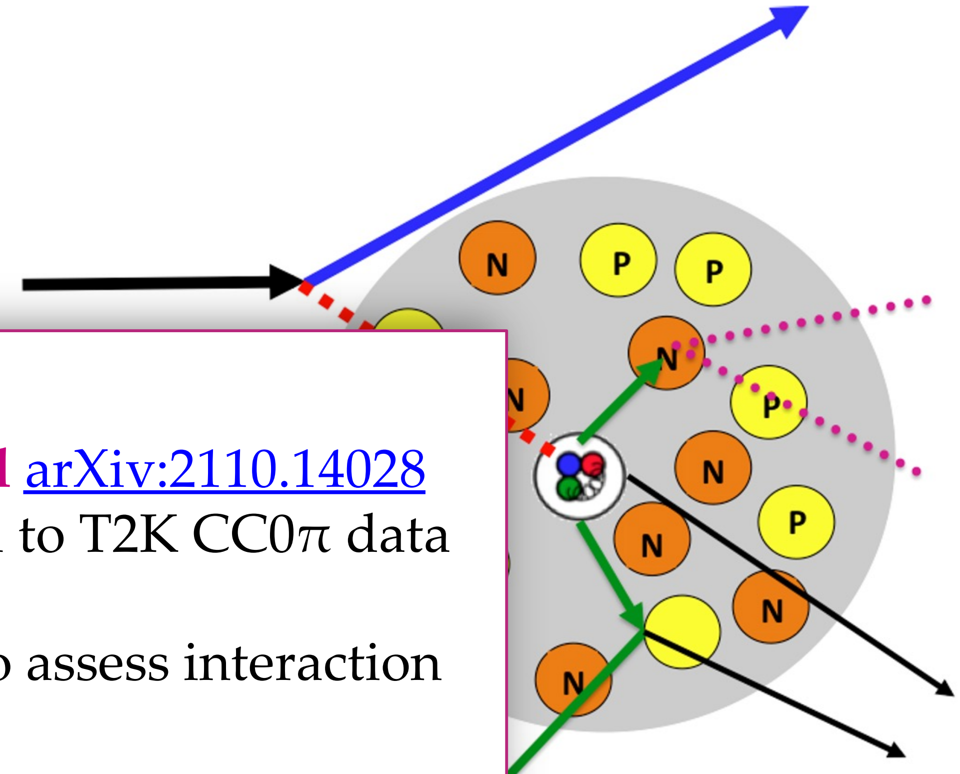
Strongly interacting nucleons
→ altera
coupl

Interacti
→ Meso
→ Short

Final St
→ re-interactions of the ν products
within the nuclear medium

Improved neutrino interaction model arXiv:2110.14028
"Theory-driven" CCQE & MEC tuned to T2K CC0π data

More than **50 parameters** are varied to assess interaction uncertainties.



Significant uncertainty in ν_e/ν_μ CC cross section models due to limited experimental data in argon at low energy ~200MeV

… so we measure our own cross sections!

Systematic uncertainties

We have made the first complete assessment of systematic uncertainties in a LArTPC

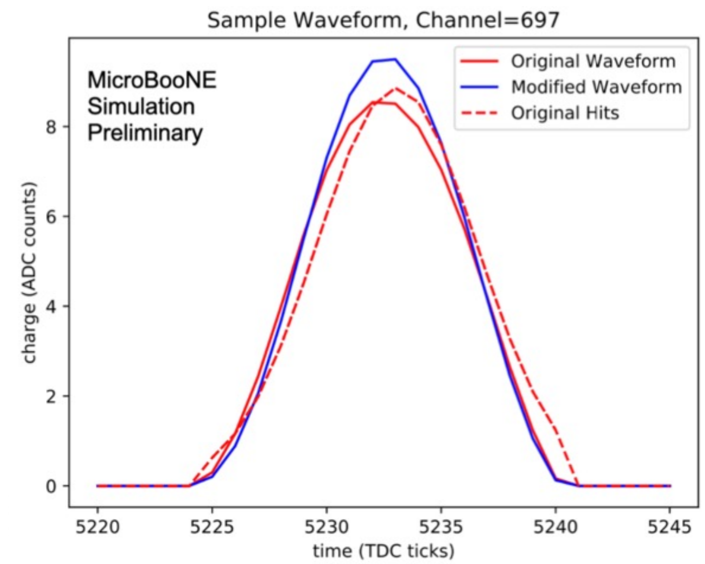
- Years of work have come to fruition

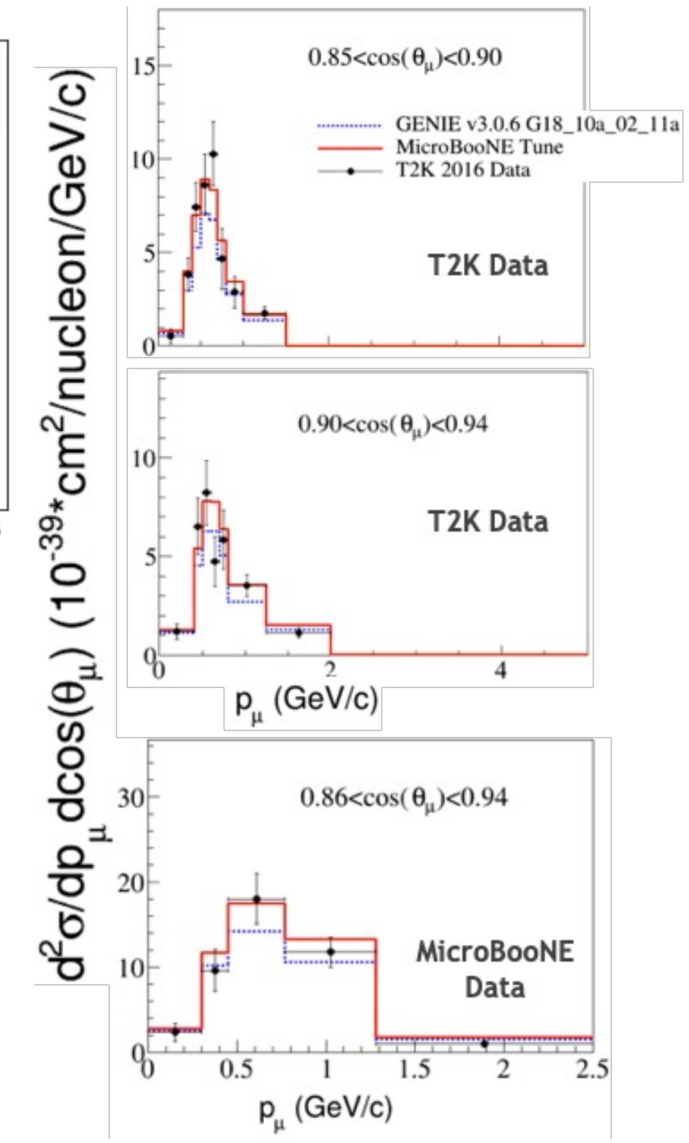
Detector uncertainties

- Novel data-driven technique using wire responses
- **arXiv:2111.03556**
- Plus evaluations of space charge, recombination, optical model & GEANT4 uncertainties

Developed our own ‘MicroBooNE GENIE tune’

- Fit to 2016 T2K ν_μ CC0π data taken at similar energies
- Tune CCQE and CC2p2h models
- Varying >50 parameters to assess interaction uncertainties
- **arXiv:2110.14028**





7

A common strategy for multiple analyses

MicroBooNE is a surface detector: Uses light + beam trigger to ID neutrinos.
Events typically contain ν + o(20) cosmic μ
→ isolate neutrino activity in active volume

ν-ID/cosmic rejection

e or γ ID

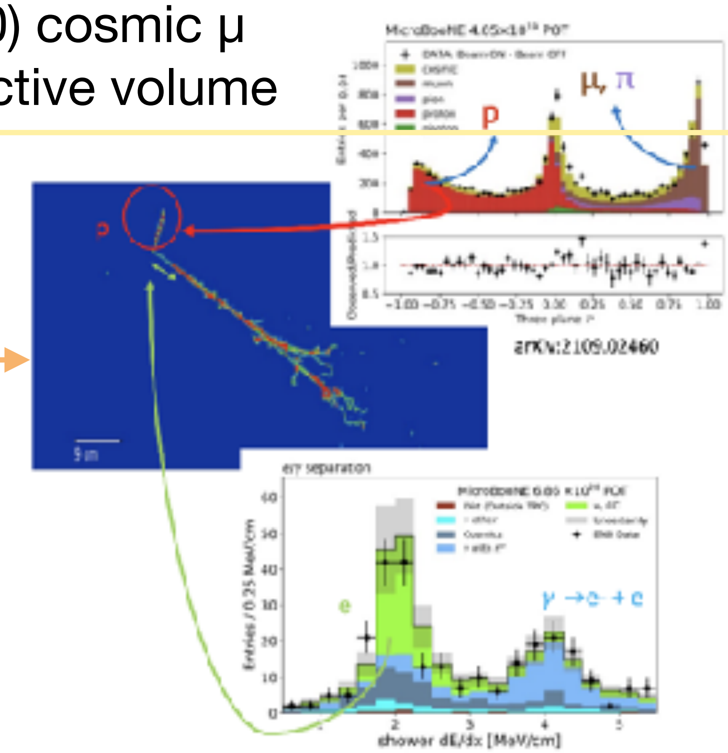
p, π tagging μ rejection

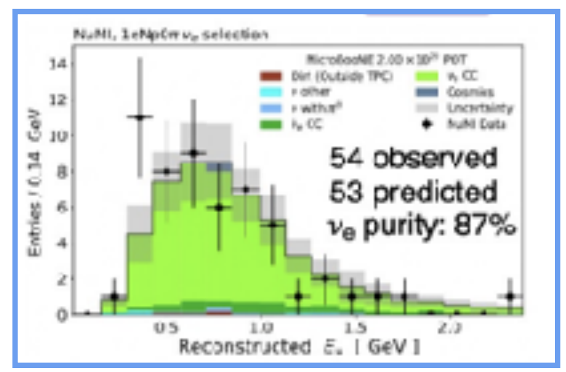
Event selection + sidebands

Constraint of systematics

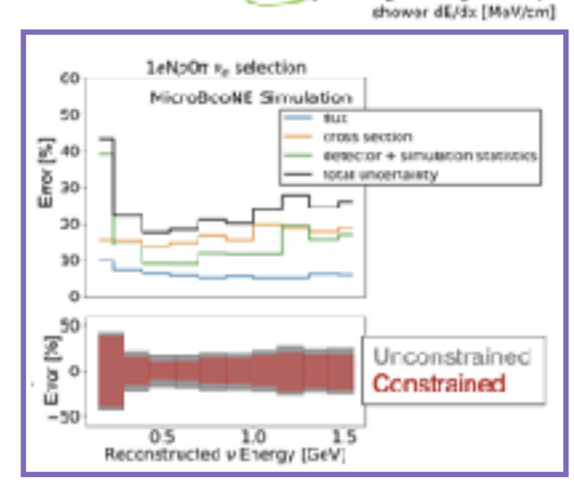
Results & Statistical Interpretation

- Hadrons/μ: likelihood based PID
- e/γ: shower dE/dx





Data in non-signal region used to validate analysis and modeling.
Selection frozen before sideband data.
Progressive unblinding



Simple Hypothesis Test: Probability of the data rejecting one hypothesis assuming the other is true, using a $\Delta\chi^2$ formalism.
Signal Strength Comparisons: Use Feldman-Cousins procedure to measure best fit signal strength

3+1 Oscillation Analysis (2)

- Use samples from ν_μ and ν_e inclusive LEE search; free fit parameters:

Δm^2_{41} $\sin^2\theta_{14}$ $\sin^2\theta_{24}$

- Cancellation of ν_e appearance and ν_e disappearance effects leads to degeneracy

Number of intrinsic ν_e in the flux

$\Delta m^2_{41} L / 4E$

$$N_{\nu_e}(E_\nu) = T_{\nu_e}(E_\nu)[1 + (R(E_\nu) \times \sin^2\theta_{24} - 1) \times \sin^2 2\theta_{14} \sin^2\Delta_{41}(E_\nu)]$$

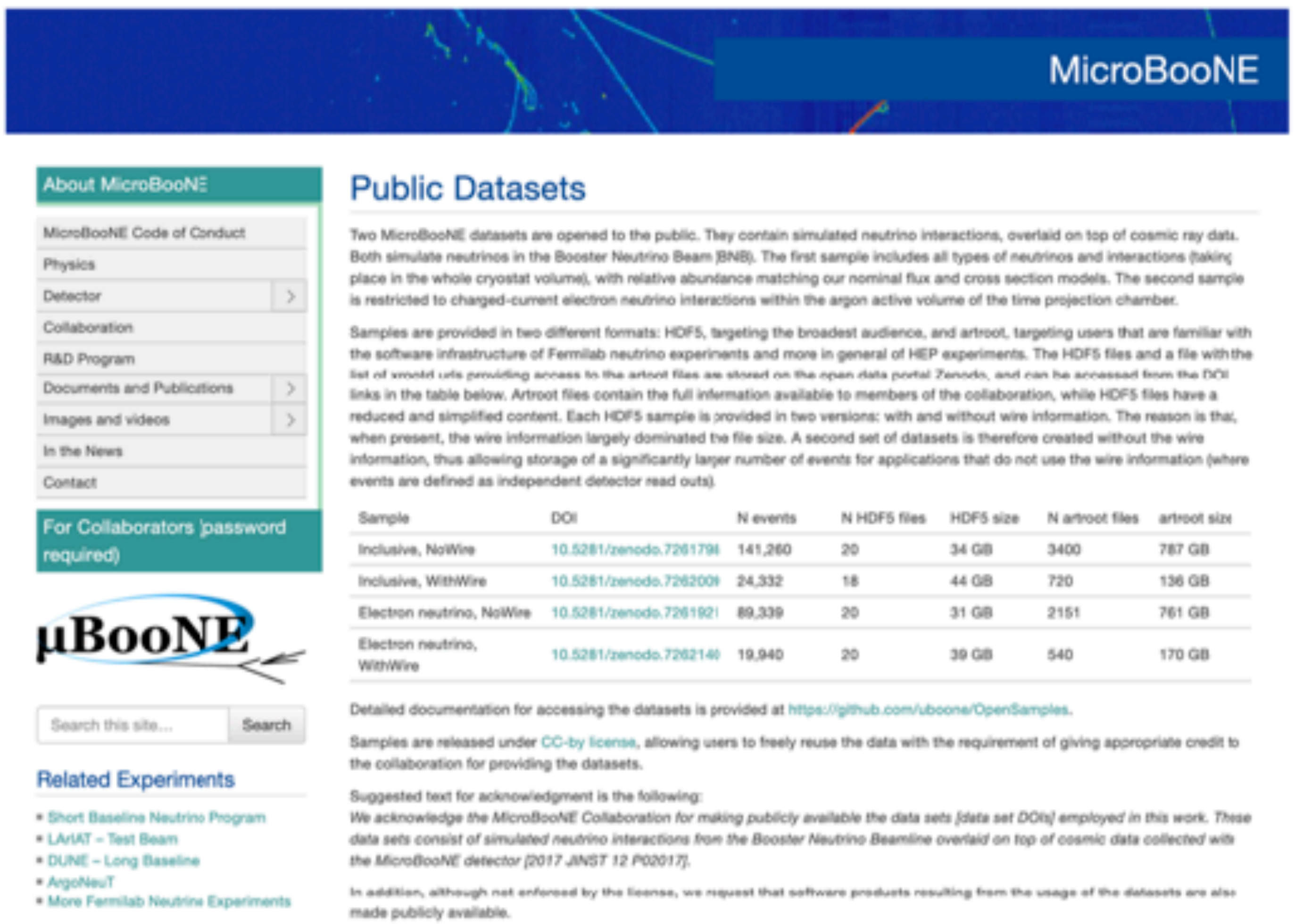
True neutrino energy

Ratio between the number of intrinsic ν_μ and ν_e

MicroBooNE Open Data

Access point

- Entry point is the MicroBooNE website:
  - https://microboone.fnal.gov/documents-publications/public-datasets/



MicroBooNE

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µBooNE

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Public Datasets

Two MicroBooNE datasets are opened to the public. They contain simulated neutrino interactions, overlaid on top of cosmic ray data. Both simulate neutrinos in the Booster Neutrino Beam (BNB). The first sample includes all types of neutrinos and interactions (taking place in the whole cryostat volume), with relative abundance matching our nominal flux and cross section models. The second sample is restricted to charged-current electron neutrino interactions within the argon active volume of the time projection chamber.

Samples are provided in two different formats: HDF5, targeting the broadest audience, and artroot, targeting users that are familiar with the software infrastructure of Fermilab neutrino experiments and more in general of HEP experiments. The HDF5 files and a file with the list of xrootd urls providing access to the artroot files are stored on the open data portal Zenodo, and can be accessed from the DOI links in the table below. Artroot files contain the full information available to members of the collaboration, while HDF5 files have a reduced and simplified content. Each HDF5 sample is provided in two versions: with and without wire information. The reason is that, when present, the wire information largely dominated the file size. A second set of datasets is therefore created without the wire information, thus allowing storage of a significantly larger number of events for applications that do not use the wire information (where events are defined as independent detector read outs).

Sample	DOI	N events	N HDF5 files	HDF5 size	N artroot files	artroot size
Inclusive, NoWire	10.5281/zenodo.7261798	141,260	20	34 GB	3400	787 GB
Inclusive, WithWire	10.5281/zenodo.7262009	24,332	18	44 GB	720	136 GB
Electron neutrino, NoWire	10.5281/zenodo.7261921	89,339	20	31 GB	2151	761 GB
Electron neutrino, WithWire	10.5281/zenodo.7262140	19,940	20	39 GB	540	170 GB

Detailed documentation for accessing the datasets is provided at https://github.com/uboone/OpenSamples.

Samples are released under CC-by license, allowing users to freely reuse the data with the requirement of giving appropriate credit to the collaboration for providing the datasets.

Suggested text for acknowledgment is the following:
We acknowledge the MicroBooNE Collaboration for making publicly available the data sets [data set DOIs] employed in this work. These data sets consist of simulated neutrino interactions from the Booster Neutrino Beamline overlaid on top of cosmic data collected with the MicroBooNE detector [2017 JINST 12 P02017].

In addition, although not enforced by the license, we request that software products resulting from the usage of the datasets are also made publicly available.

Description

Links to Zenodo

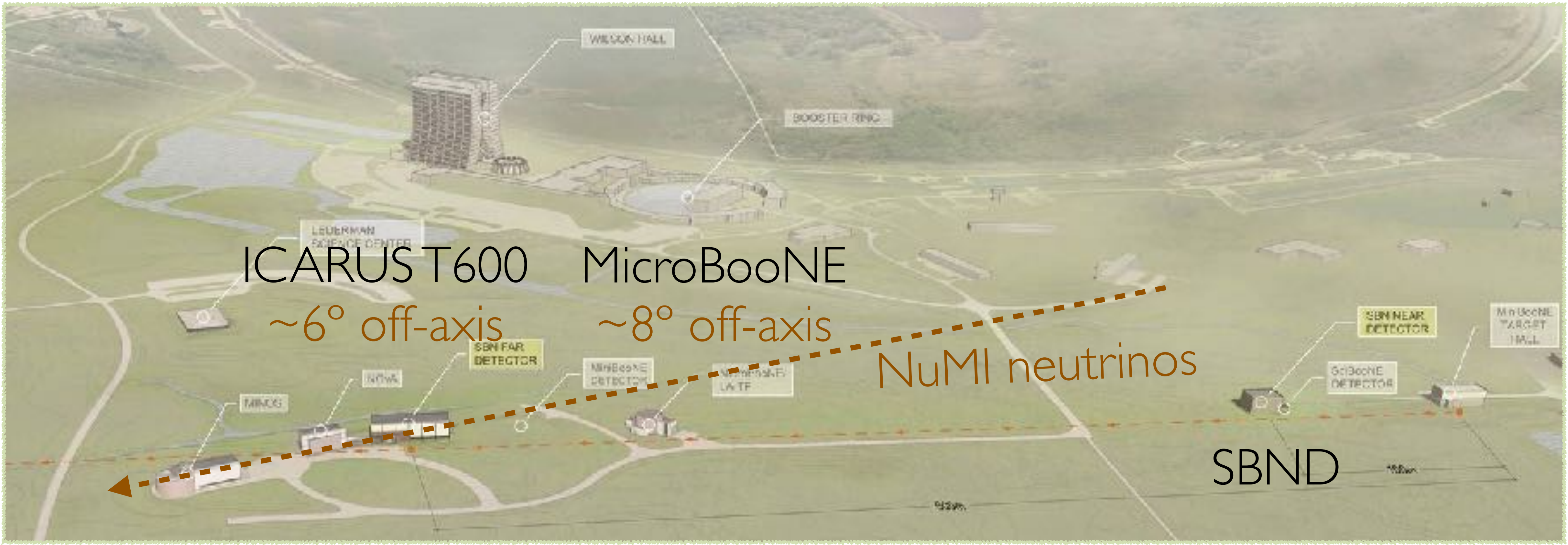
Link to documentation

Info about license and citation

Fermilab

10 2023/05/09 G. Cerati (FNAL)

Free Neutrinos from NuMI



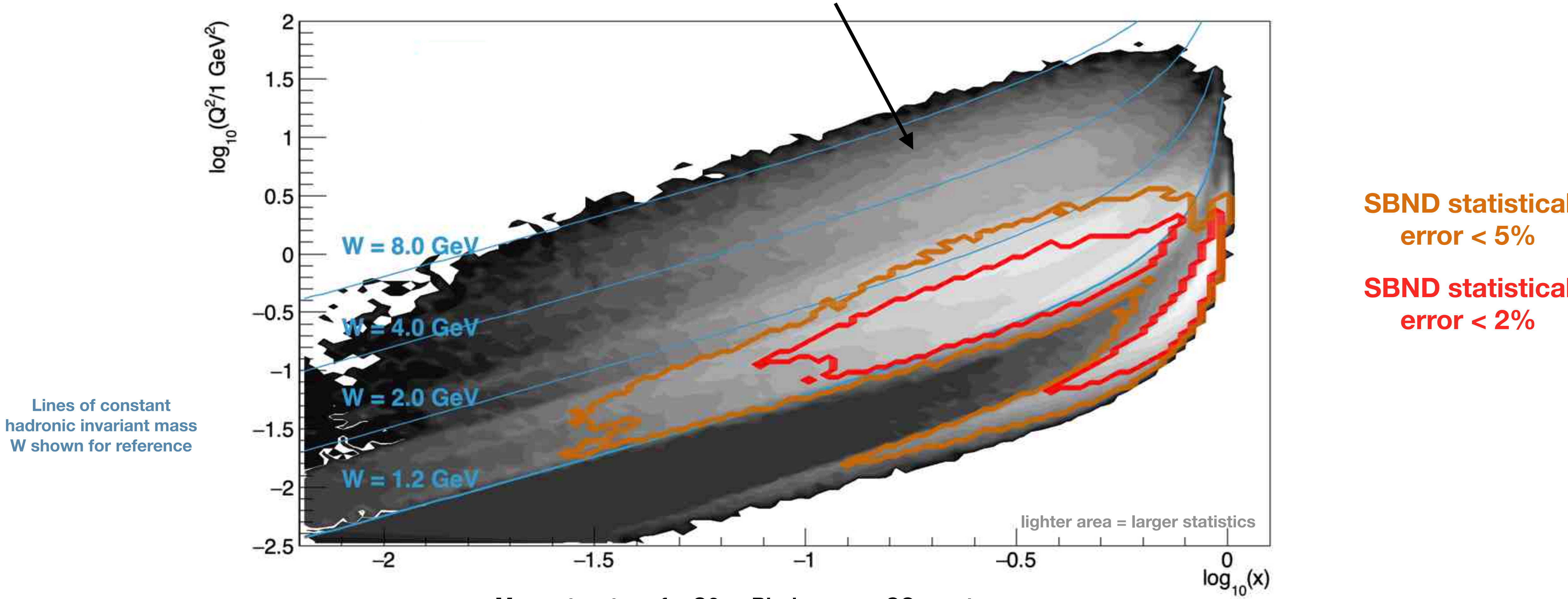
- NuMI ν_μ: 120 GeV protons
- Off-axis neutrino beams for MicroBooNE and ICARUS
- ν-Ar cross section measurements
- BSM searches from both BNB and NuMI

Cross section measurements

- SBND's vicinity to neutrino target it will allow measurements of many rare channels such as heavy baryons (Δ^0, Σ^+), NC coherent single photon production, etc.

- SBND covers peaks of kinematic area relevant for DUNE.

Kinematical coverage of LBNF (DUNE) beam



Momentum transfer Q2 vs Bjorken x - ν_μ CC events