MicroBooNE in 10 minutes

Guanqun Ge, Columbia University
On behalf of the MicroBooNE collaboration

New Perspectives
August 17th, 2021

Overview

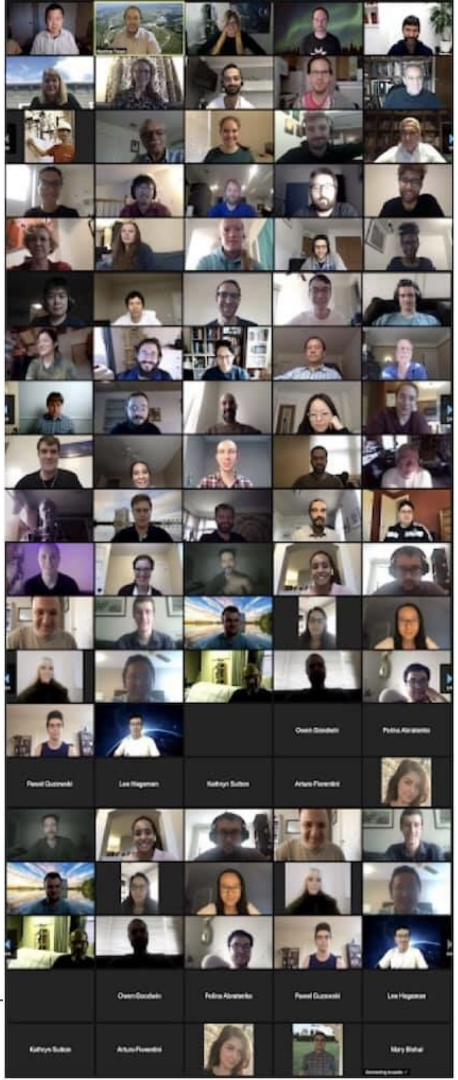
μBooNE is a liquid argon time projection chamber (LArTPC) detector experiment based at Fermilab, and has been in operation since October 2015

This talk will give a brief overview of the MicroBooNE experiment, how it works and interesting physics research done with MicroBooNE data

Detector going in to the building!!

MicroBooNE collaboration photon taken on Oct 9, 2014

Collaboration photo taken in Oct 2020

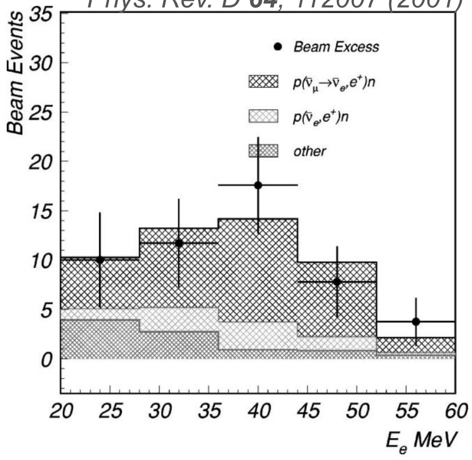


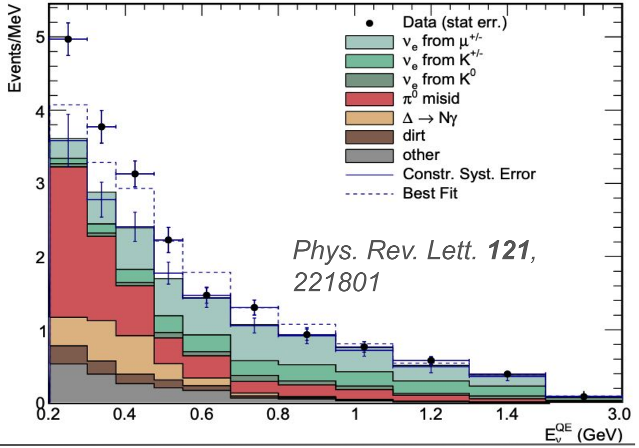
The “Low-Energy-Excess” (LEE) Anomaly

- A 3.8σ excess is observed anti-ν_e charge-current quasielastic (CCQE) events by the Liquid Scintillation Neutrino Detector (LSND) experiment in anti-$\nu_\mu \rightarrow$ anti-ν_e oscillation measurement using anti-ν_μ from μ^+ decay at rest, suggesting neutrino oscillations occur with Δm^2 of 0.2~10 eV^2

- Later a similar picture is seen in MiniBooNE in both ν_e and anti-ν_e appearance measurements
  - 4.7σ excess is observed in ν_e and anti-ν_e CCQE events, which can not be explained by nominal 3 neutrino (ν_e , ν_μ , ν_τ) oscillation
  - MiniBooNE (ran from 2002 to 2017) is a Cherenkov detector, thus not able to distinguish photons from electrons

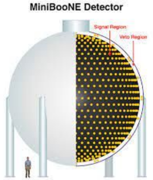
Phys. Rev. D ***64****, 112007 (2001)*

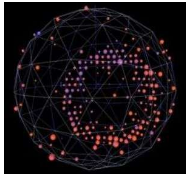




Phys. Rev. Lett. ***121****, 221801*

CR: Fermilab

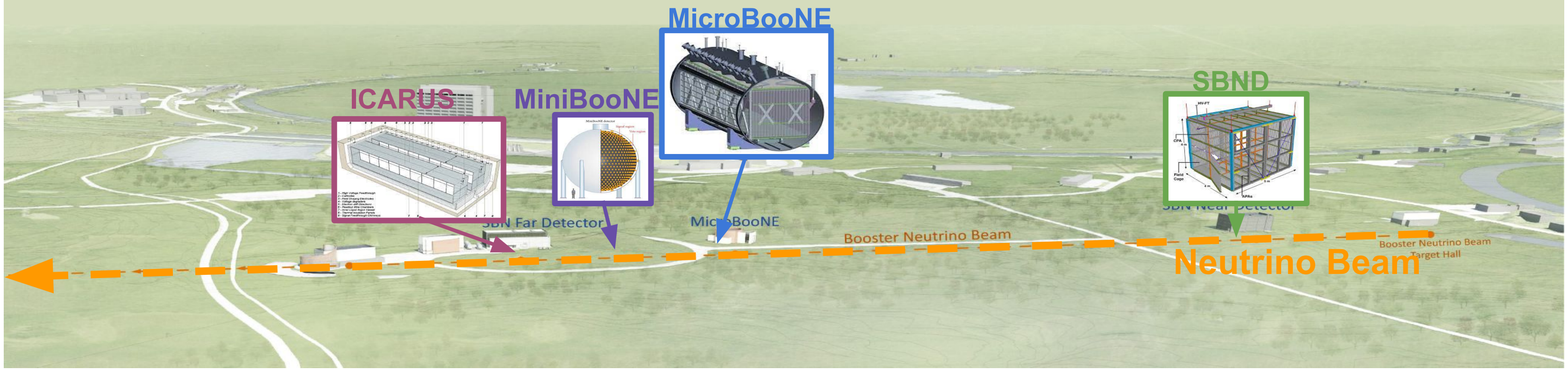




The MicroBooNE experiment

The MicroBooNE experiment was proposed to **resolve the MiniBooNE LEE anomaly**, **measure neutrino-argon interactions** and to **pave the way for future LArTPC programs and experiments** such as the short-baseline neutrino (SBN) program (including SBND, ICARUS) and DUNE.

MicroBooNE is in the same beamline as the SBN program which will allow very sensitive neutrino oscillation measurements explicitly due to high-Δm^2 oscillations associated with additional mostly sterile neutrinos, which is one possible interpretation of the LSND and MiniBooNE anomalies.

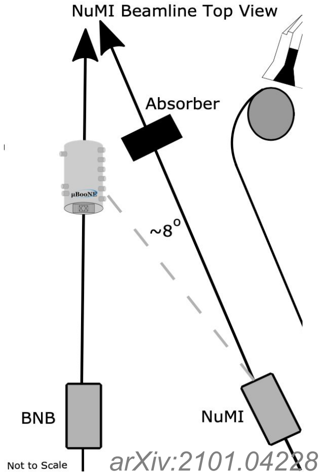


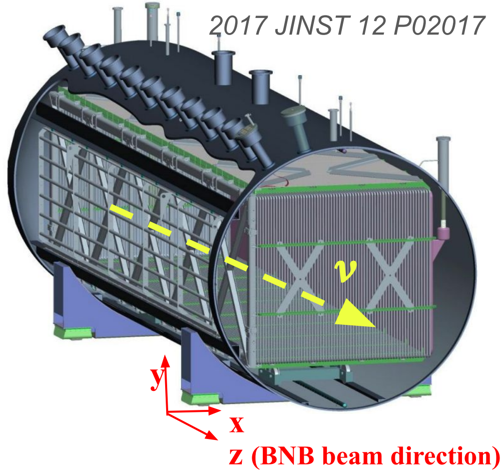
The MicroBooNE experiment

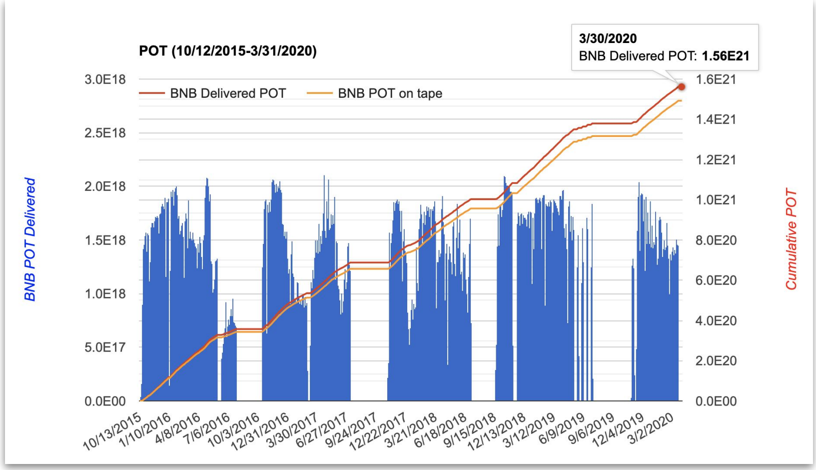
The MicroBooNE detector is

- 10.36 (z) × 2.56 (x) × 2.32 (y) m^3
- inside a cryostat with an active mass of 85 tons of liquid argon
- exposed to two neutrino beams: on-axis 470m downstream of the Booster Neutrino Beam (BNB), and off-axis neutrinos from the Main Injector (NUMI) neutrino beam
    - BNB beam has a high purity of ν_μ and anti-ν_μ (>99%) while NUMI has a ν_e component 10x larger than BNB

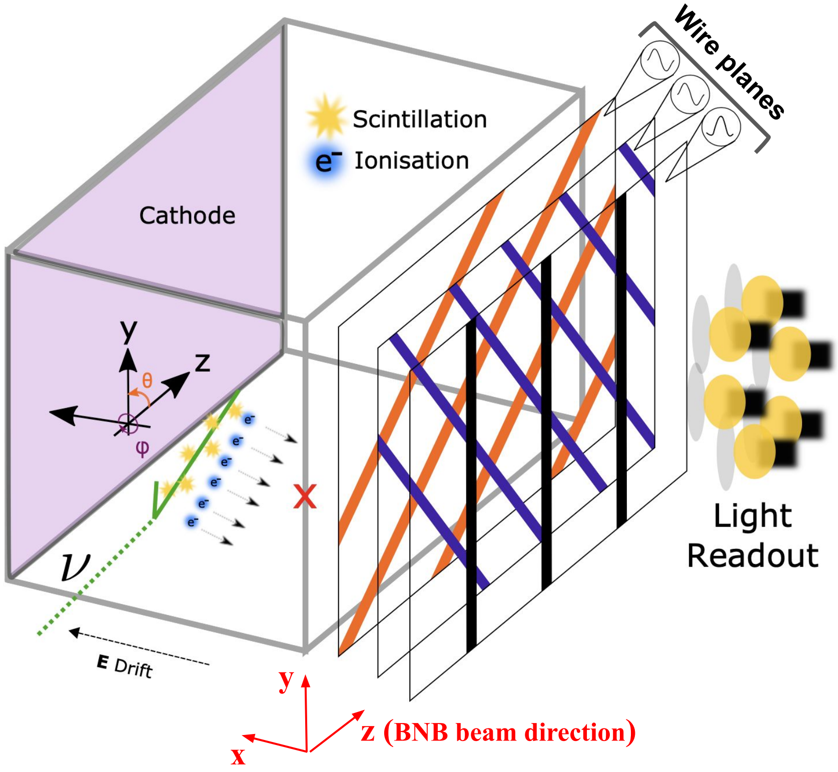
MicroBooNE has completed its 5 years physics run from 2015-2020, yielding the largest neutrino-argon dataset!







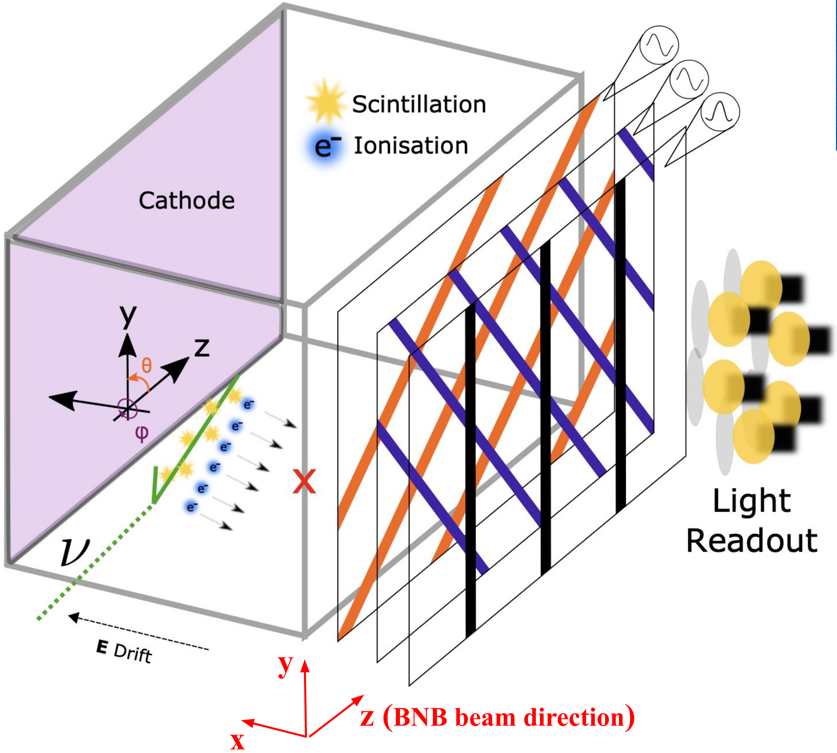
LArTPC working principle



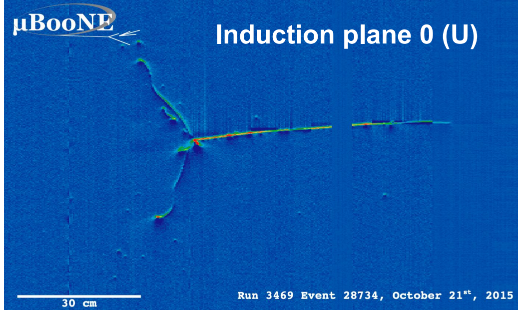
arXiv:2101.04228

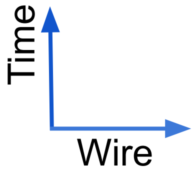
1. When neutrinos enter the detector: if lucky one of them interacts with argon atom, generating daughter particles (neutral or charged)
2. Charged final state particles ionize and excite the argon atoms while traversing through liquid argon, which generates ionization electrons and scintillation light
3. Under the uniform electric field, electrons drift from point of generation to the anode consisting of three wire planes, inducing signals on certain wires
4. Scintillation light is collected by the photomultiplier tubes (PMTs) behind the anode plane, providing the start time of the interaction
5. Knowing the time of the interaction and the position of the "hit" wires, it's sufficient to infer place of generation for the particles

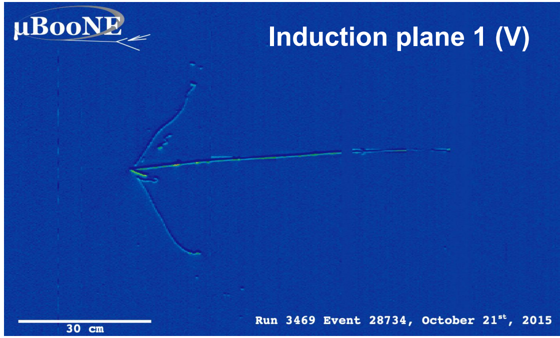
LArTPC working principle

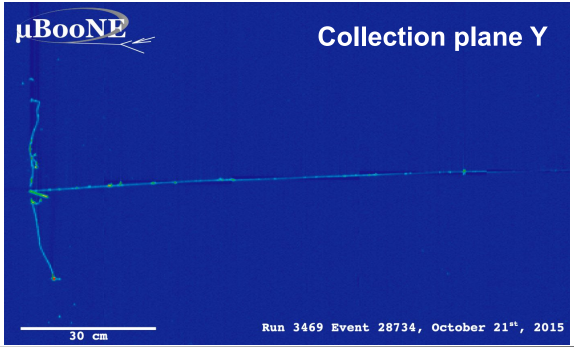


arXiv:2101.04228





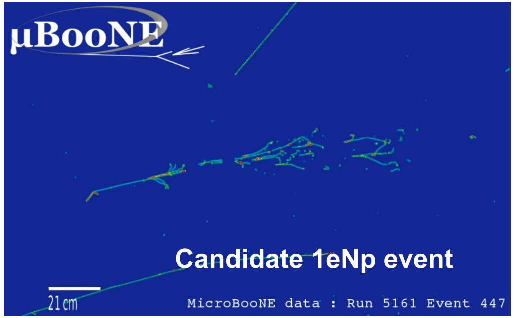




MicroBooNE's Low-Energy Excess Search

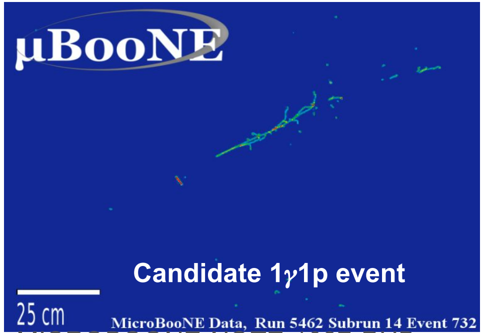
One of MicroBooNE's primary physics goals is to explore the LEE under two main hypotheses:

- **Excess in electrons**
  - Excess in electrons may imply an increased oscillation probability with high-Δm^2 , which could be associated with additional neutrino beyond three neutrinos, or other interesting physics
  - Model targeted by MicroBooNE is an energy-dependent modification to the ν_e



MICROBOONE-NOTE-1085-PUB

- **Excess in photons**
  - Excess in photons could come from SM processes that are not correctly modeled in the event simulation or from beyond SM physics
  - Model targeted by MicroBooNE is the photon excess from neutral current (NC) Δ resonance (1232MeV) radiative decay



MICROBOONE-NOTE-1087-PUB

MicroBooNE's Low-Energy Excess Search

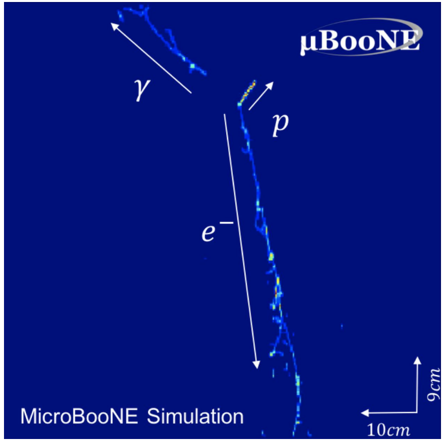
With entire detector as a calorimeter, MicroBooNE enables the differentiation of electron from photon through displacement of shower start from the interaction vertex, and the 2x energy deposition at the start of photon shower compared to electron shower.

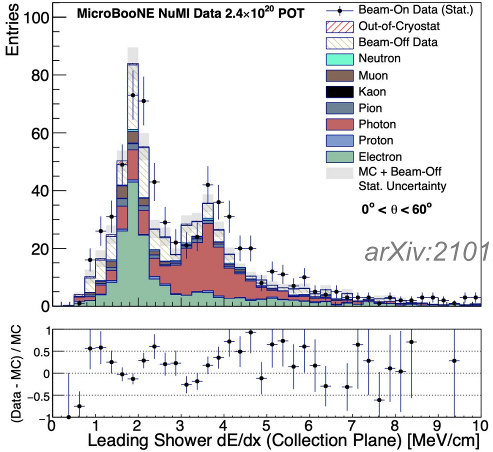
MicroBooNE will explore the LEE under two main hypotheses:

- **Excess in electrons**
    - Pandora pattern recognition, targeting 1eNp (N>1), 1e0p
    - Deep learning based classification, targeting 1e1p (ν_e CCQE)
    - Wire-Cell based event reconstruction, targeting 1eX (inclusive ν_e CC)
- **Excess in photons**
    - Pandora pattern recognition, targeting NC $\Delta \rightarrow$ N+γ

MicroBooNE Talk:
"Search for a Single Photon Anomalous Excess in MicroBooNE"
- Guanqun Ge

PHYS. REV. D 103, 092003 (2021)





arXiv:2101.04228

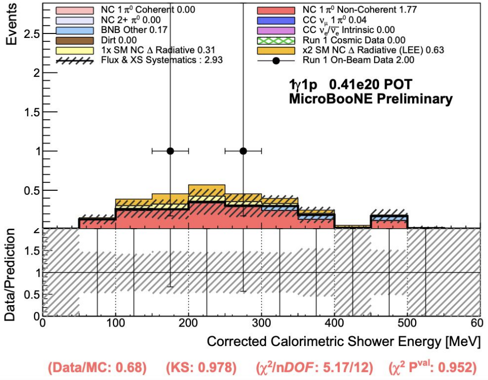
MicroBooNE's Low-Energy Excess Search

Due to blind analysis policy, only a subset of the full MicroBooNE dataset is exposed during analysis tool development stage.

Shown below are data to MC comparisons for four analyses, all four are in the final stages and we look forward to bringing out our first LEE results to the world soon!

$1\gamma1p$, BNB, open data

MICROBOONE-NOTE-1087-PUB



1eNp, Pandora, BNB, >1.05GeV

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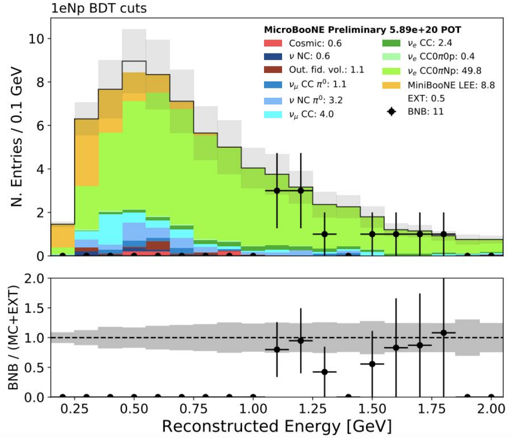

1eX, Wire-Cell, NUMI

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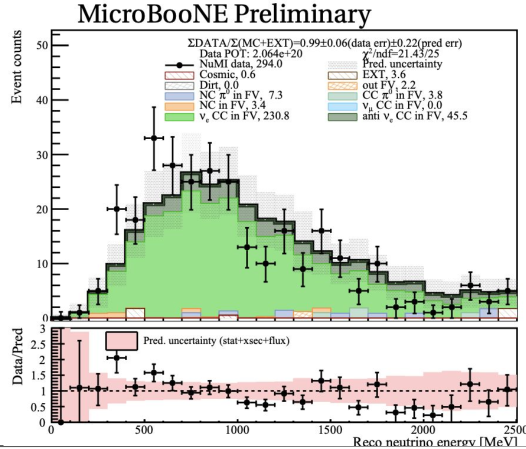
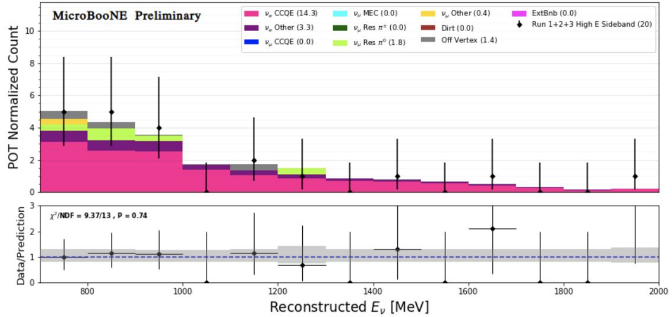


1e1p, DL, BNB, >700MeV

MICROBOONE-NOTE-1086-PUB

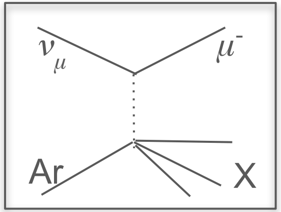


Cross section measurement

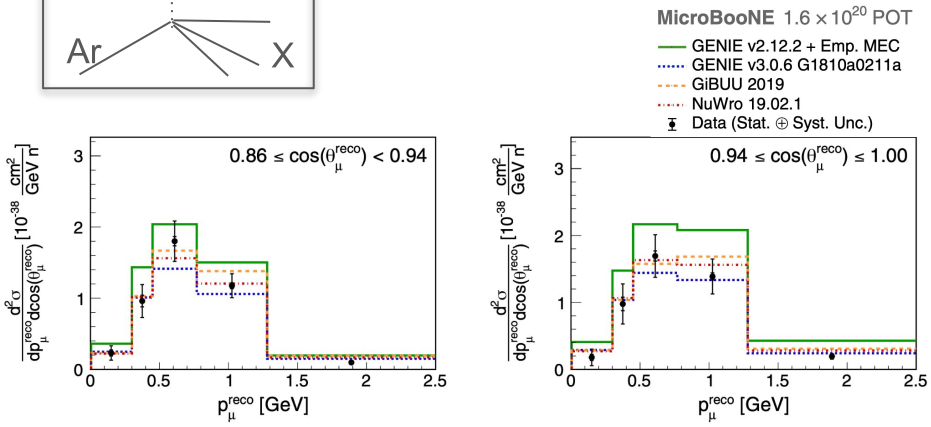
Comprehensive theoretical and experimental understanding of neutrino interaction with detector target is essential for neutrino measurements. With BNB and NUMI data, MicroBooNE has measured the interaction cross section for both ν_μ and ν_e neutrino interactions.

ν_μ charge-current (CC) inclusive measurement using BNB

- ν_μ CC interaction is highly correlated with ν_e CC interaction which is important to study the MiniBooNE LEE
- Require 1 muon track + X
- Yield 50.4% purity and 57.2% efficiency for ν_μ CC interactions
- Disagreements between the data and predictions in the high-momentum bins in the most forward-going muon angular bins
- GENIE v3 model gives the least tension overall



$\sigma(\nu_\mu + \text{Ar} \rightarrow \mu^- + \text{X})$ per nucleon:
0.693 ± 0.010 (stat) ± 0.165 (syst) $\times 10^{-38}$ cm^2



Phys. Rev. Lett. ***123***, *131801(2019)*

Cross section measurement

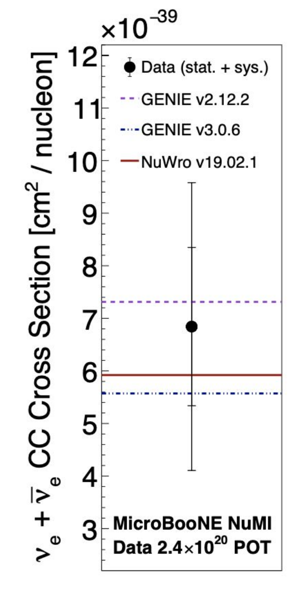
..And many more!

BNB

- ν_μ CC $1\pi^0$+X *Phys. Rev. D **99**, 091102(R)*
- ν_μ CC Np0π (N>0) *Phys. Rev. D **102**, 112013*
- Inclusive ν_μ CC (1μ + X) *Phys. Rev. Lett. **123**, 131801*
- ν_μ CCQE (1μ1p) *Phys. Rev. Lett. **125**, 201803*
- ν_μ neutral current (NC)1p *MICROBOONE-NOTE-1067-PUB*
- …

NUMI

- Inclusive ν_e and anti-ν_e CC
  arXiv:2101.04228
- ν_e CC 1eNp exclusive
- Inclusive anti-ν_e
- …



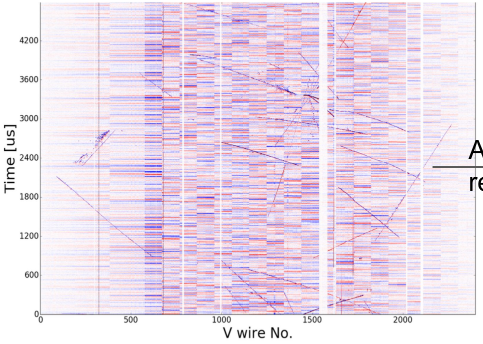
arXiv:2101.04228

MicroBooNE Talks:
"Towards The First Measurement of Differential Charged Current Single Transverse Variable ν_μ-Argon Scattering Cross Sections with the MicroBooNE Detector"
- Afroditi Papadopoulou
"Extraction of the Inclusive Muon Neutrino Charged Current Cross Section at MicroBooNE using Wiener SVD Unfolding " **- London Cooper-troendle**

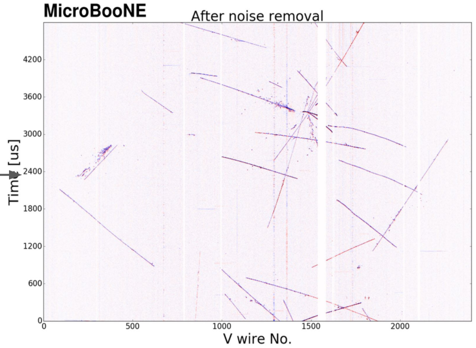
Signal Processing

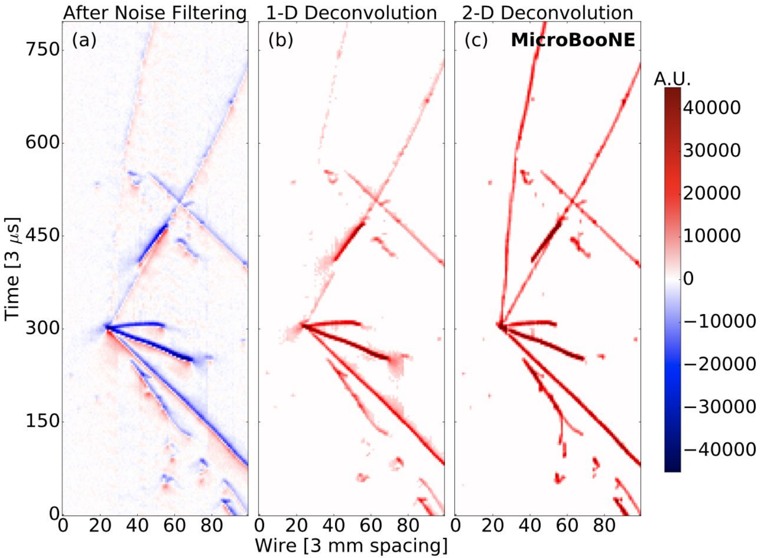
Raw digitized waveform readout by electronics is result of convolution of ionization charge distribution, electron drifting inducing current on wires and the electronics response, together with inherent electronic noises. To clearly match the raw waveform to the drifting ionization charge, MicroBooNE has done pioneering work in

- Excess noise removal *2017 JINST 12 P08003*
- Improved field & electronic response simulation
- 2D waveform deconvolution
  2018 JINST 13 P07006 & 2018 JINST 13 P07007



After noise removal

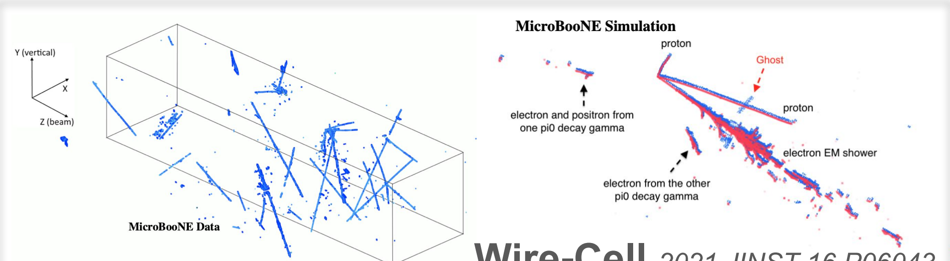




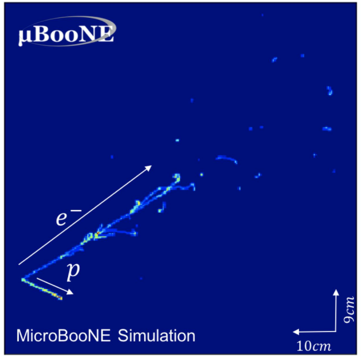
Event Reconstruction

Several different, independent event reconstruction techniques have been developed/utilized for MicroBooNE analyses:

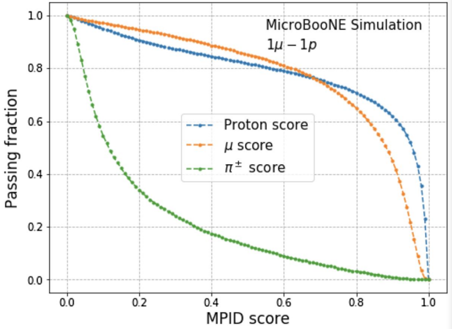
- Pandora pattern recognition
- Convolutional neural network
- Wire-Cell 3D imaging, clustering



Wire-Cell *2021 JINST 16 P06043*

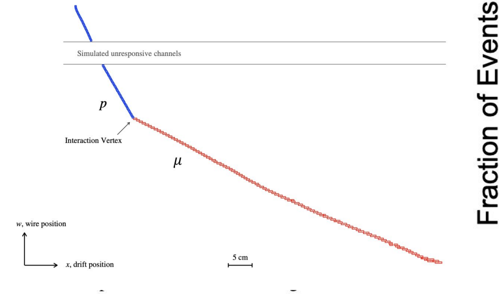


	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.99	0.98	0.06	0.01	0.02

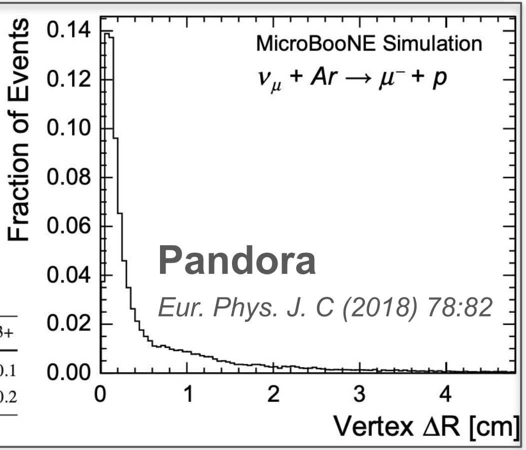


Deep Learning

Phys. Rev. D ***103****, 092003 (2021)*



# Matched particles	0	1	2	3+
μ (%)	1.3	95.8	2.9	0.1
p (%)	8.9	87.3	3.6	0.2



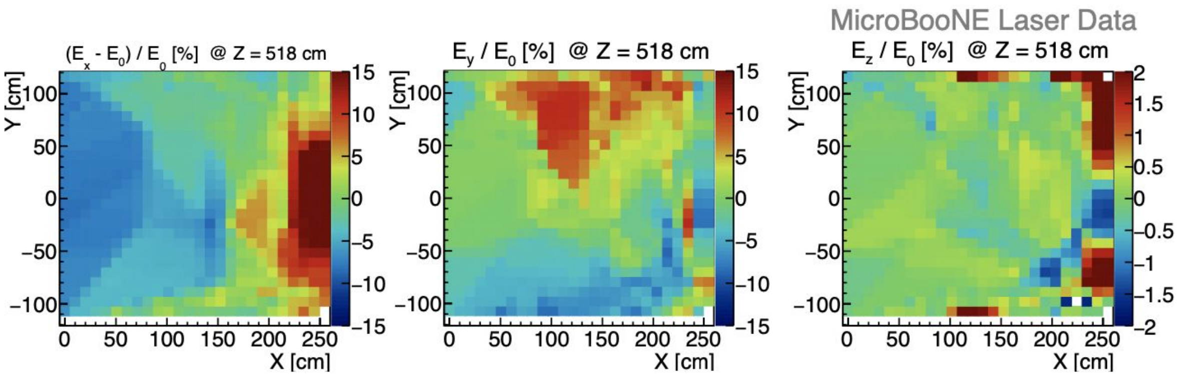
Pandora

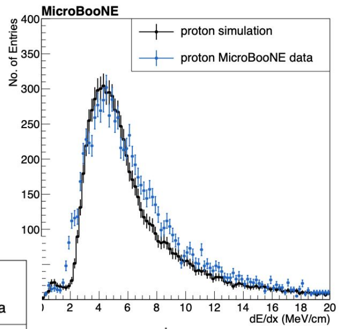
Eur. Phys. J. C (2018) 78:82

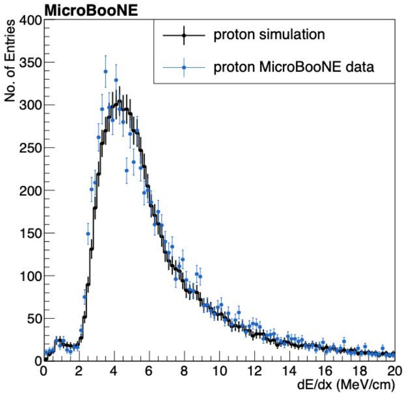
Detector Physics

Additionally, we have done a lot of work in understanding various detector effects:

- Space-Charge Effect and E-field measurement 2020 JINST 15 P12037 & *2020 JINST 15 P07010*
- Performed charge and energy loss calibration *2020 JINST 15 P03022*
- Measured effective longitudinal electron diffusion coefficient *arXiv:2104.06551*
- ...







Charge calibration and MicroBooNE parameter

MicroBooNE Talk:
"Measuring the Energy Resolution of MicroBooNE at the MeV-Scale"
- Elise Chavez

Summary

MicroBooNE is a liquid argon time projection chamber detector with currently world's largest ν-argon interaction data.

Pioneering work is being done in MicroBooNE in addressing the MiniBooNE LEE anomaly, neutrino interaction measurements, event reconstruction, detector calibration and many other areas, which is important for future neutrino and LArTPC experiments!

Backup

Neutrino Oscillation

Neutrinos oscillate because their flavor eigenstates are a linear combination of mass eigenstates, according to quantum physics. When neutrinos interact with materials (make a “measurement”), there are different possibility with which different flavor eigenstates are measured.

Assume simple 2 neutrino picture where ν_α and ν_β and flavor eigenstates and ν_1 and ν_2 are mass eigenstates:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

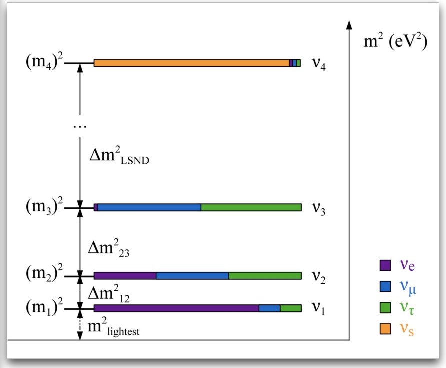
1. Probability of ν_α oscillating into ν_β is:

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(1.27\ \Delta m_{ij}^2\ (\mathrm{eV}^2)\ \frac{L(\mathrm{m})}{E(\mathrm{MeV})} \right)$$

2. Nominal three (3) neutrinos are measured to have $\Delta m_{32}^2 \sim O(10^{-3})\ \mathrm{eV}^2$, $\Delta m_{21}^2 \sim O(10^{-5})\ \mathrm{eV}^2$

https://pdg.lbl.gov/2019/reviews/rpp2018-rev-neutrino-mixing.pdf

Assume additional 1 sterile neutrinos (3+1 model):



$$P(\nu_\mu \to \nu_e) = \boxed{\sin^2(2\theta_{\mu e})} \sin^2\left(\frac{1.27\Delta m_{41}^2 L}{E}\right)$$

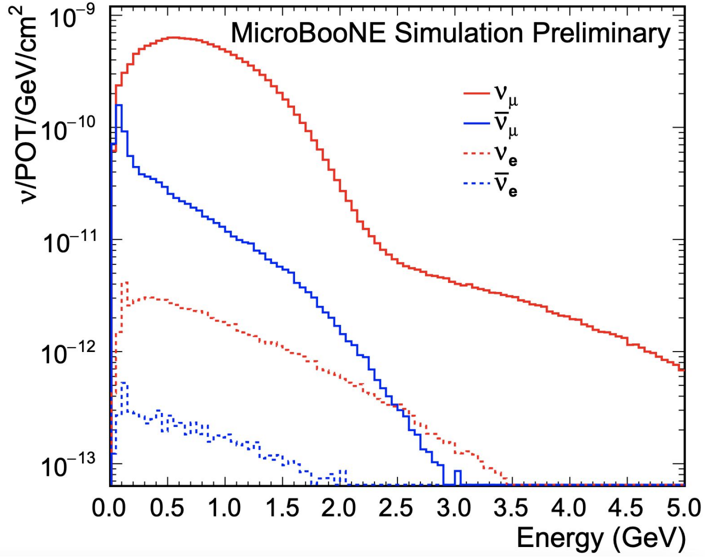
$$\boxed{\sin^2(2\theta_{\mu e}) = 4|U_{\mu 4}|^2|U_{e4}|^2}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2(2\theta_{\mu\mu})} \sin^2\left(\frac{1.27\Delta m_{41}^2 L}{E}\right)$$

$$\boxed{\sin^2(\theta_{\mu\mu}) = 4(1-|U_{\mu 4}|^2)|U_{\mu 4}|^2}$$

Neutrino Flux at MicroBooNE

BNB



NUMI