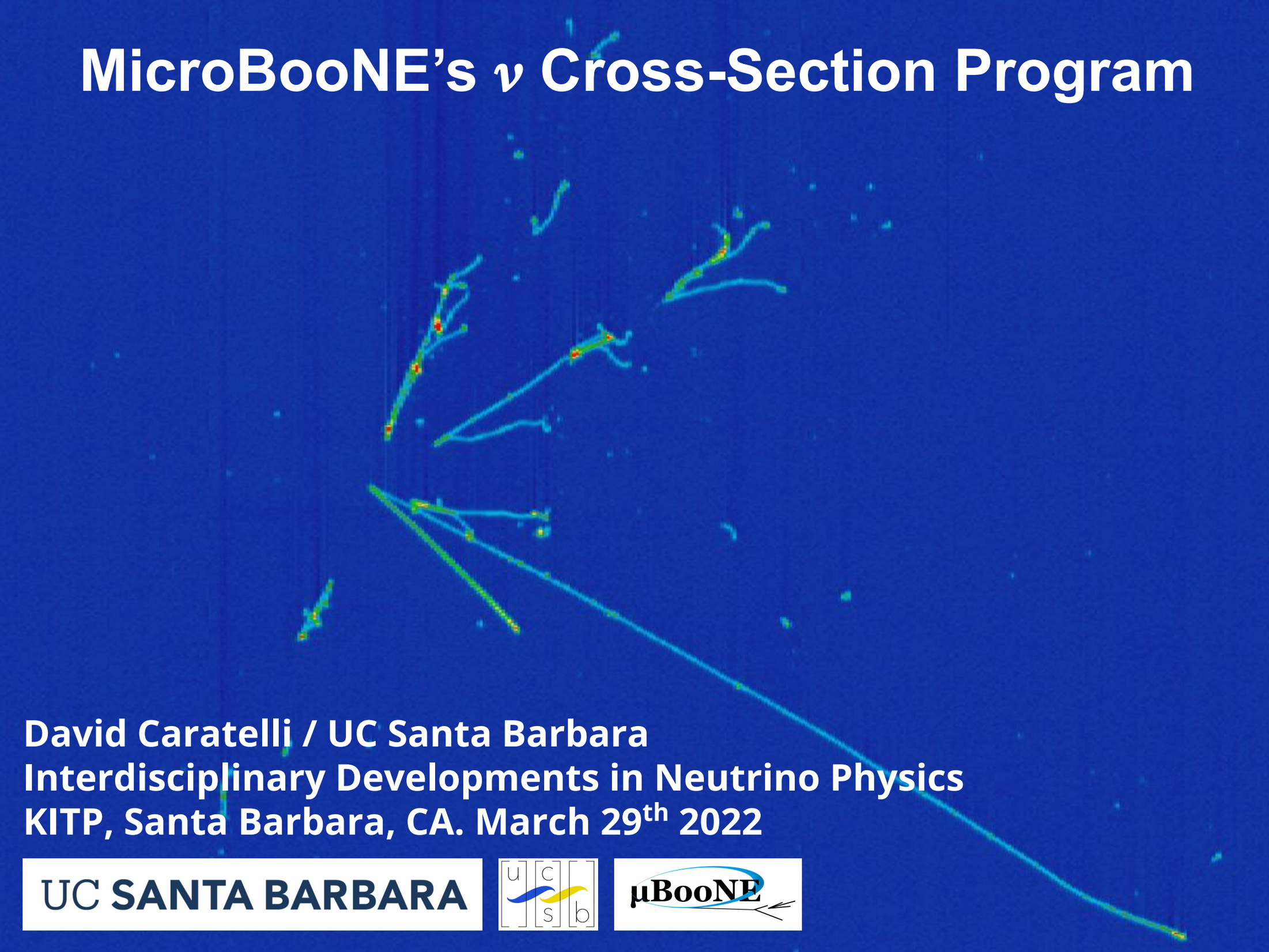
MicroBooNE's ν Cross-Section Program



David Caratelli / UC Santa Barbara

Interdisciplinary Developments in Neutrino Physics

KITP, Santa Barbara, CA. March 29th 2022

UC SANTA BARBARA

u c s b

µBooNE

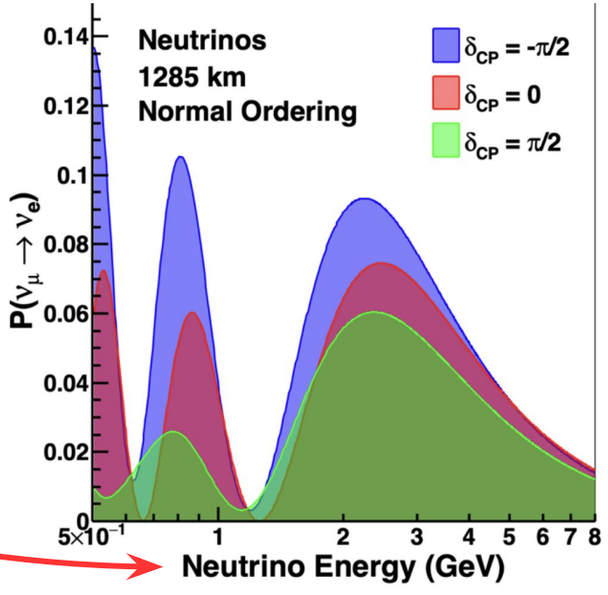
Broader Context for Cross-Section Program

Freq. Of oscillation.
Choose L, E appropriate for Δm^2.

$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

sets amplitude of oscillation.
large → "easy" to detect.

DUNE, Eur.Phys.J.C 80 (2020) 10, 978



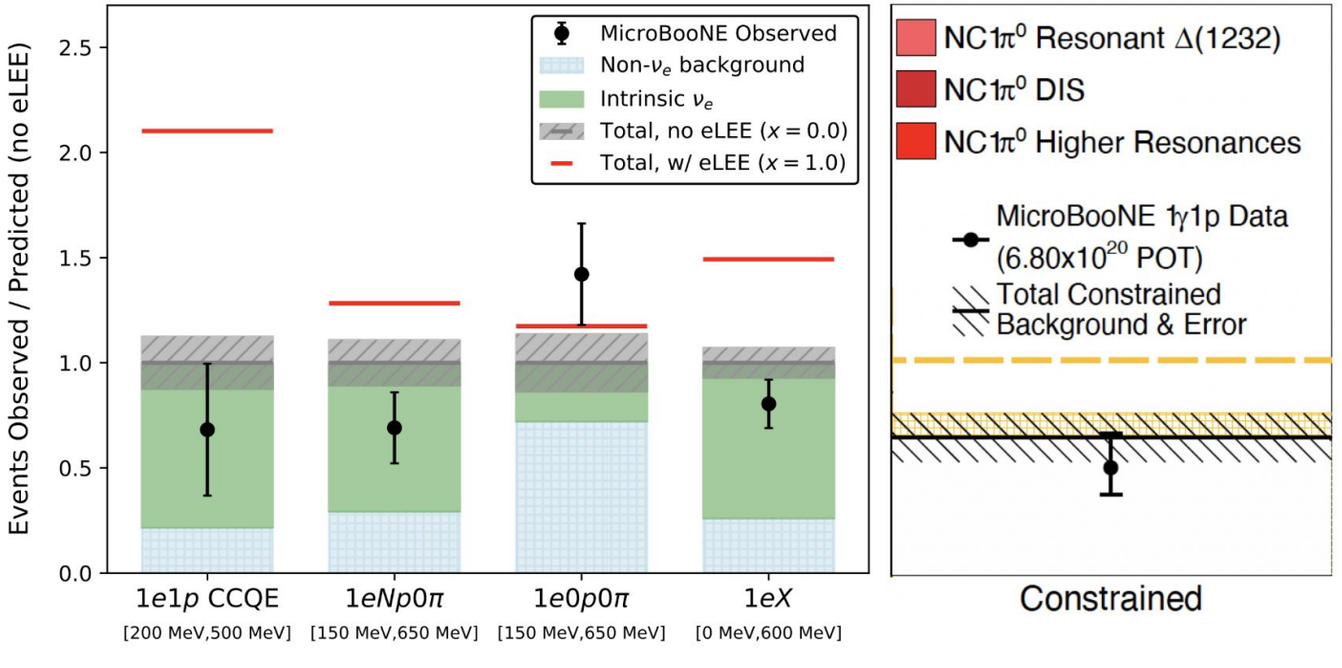
MicroBooNE results on "Low-Energy-Excess":

PRL 128 (2022) 11, 111801
arXiv:2110.14054 [PRL]

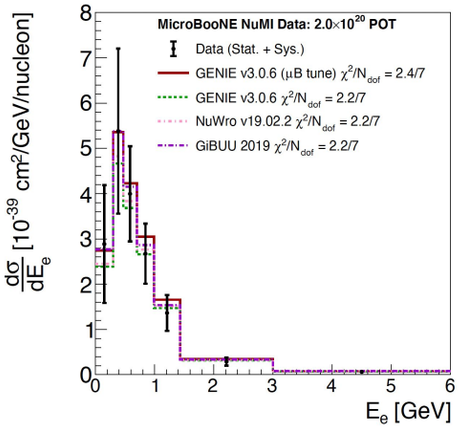
See talk by Ornella Palamara on Monday

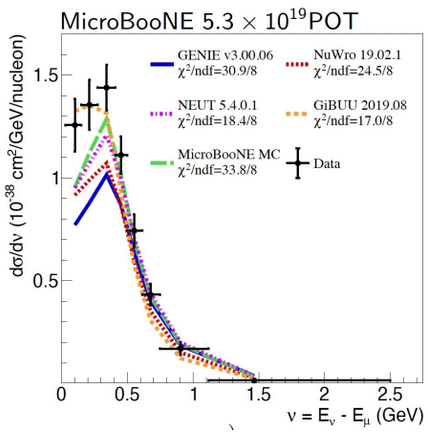
← ν_e →

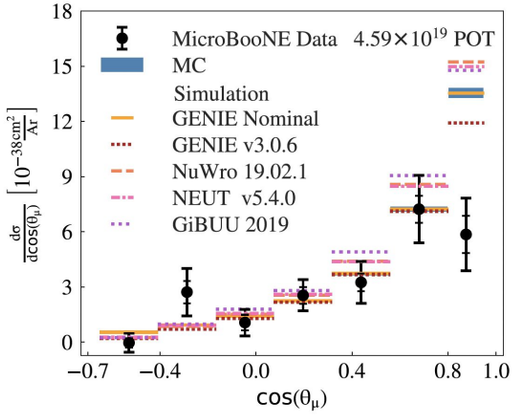
$\Delta \rightarrow \gamma$

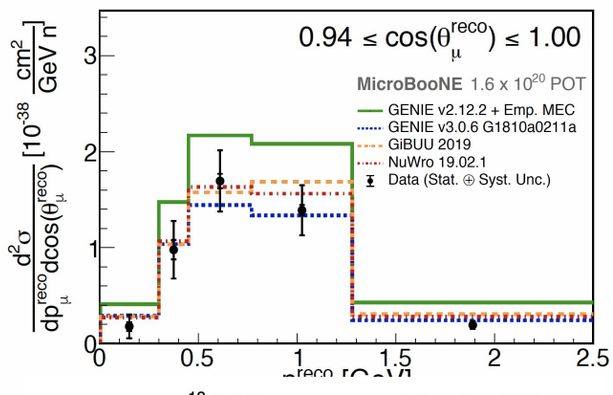


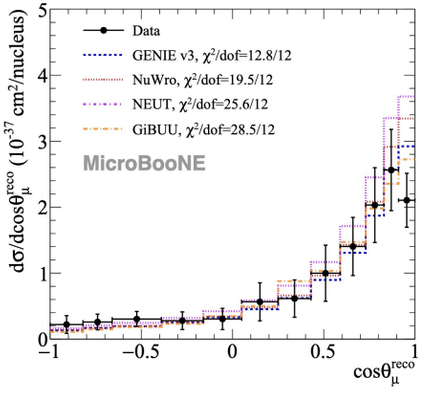
MicroBooNE's Cross-Section Program

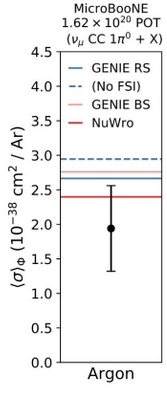


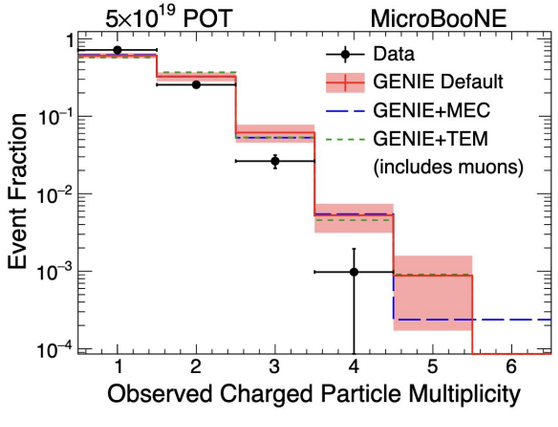


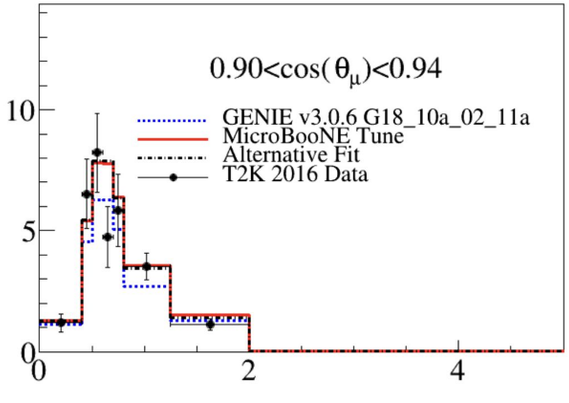












extensive xsec program performing high-statistics measurements of neutrino interactions on argon

MicroBooNE xsec measurements:

ν_μ CC Np0π [1D differential]
Phys.Rev.D 102 (2020) 11, 112013

ν_μ CCQE-like [1D differential]
Phys.Rev.Lett. 125 (2020) 20, 201803

ν_μ CC inclusive [2D differential]
Phys.Rev.Lett. 123 (2019) 13, 131801

ν_μ CC π^0 [integrated]
Phys.Rev.D 99 (2019) 9, 091102

ν_e CC [inclusive]
Phys.Rev.D 104 (2021) 5, 052002

ν_e CC [1D differential]
Phys.Rev.D 105 (2022) 5, L051102

ν_μ CC inclusive [1D differential]
arXiv:2110.14023 [accepted by PRL]

Proton multiplicity
Eur.Phys.J.C 79 (2019) 3, 248

GENIE-tune paper
arXiv:2110.14028 [accepted to PRD]

… and many more in the pipeline

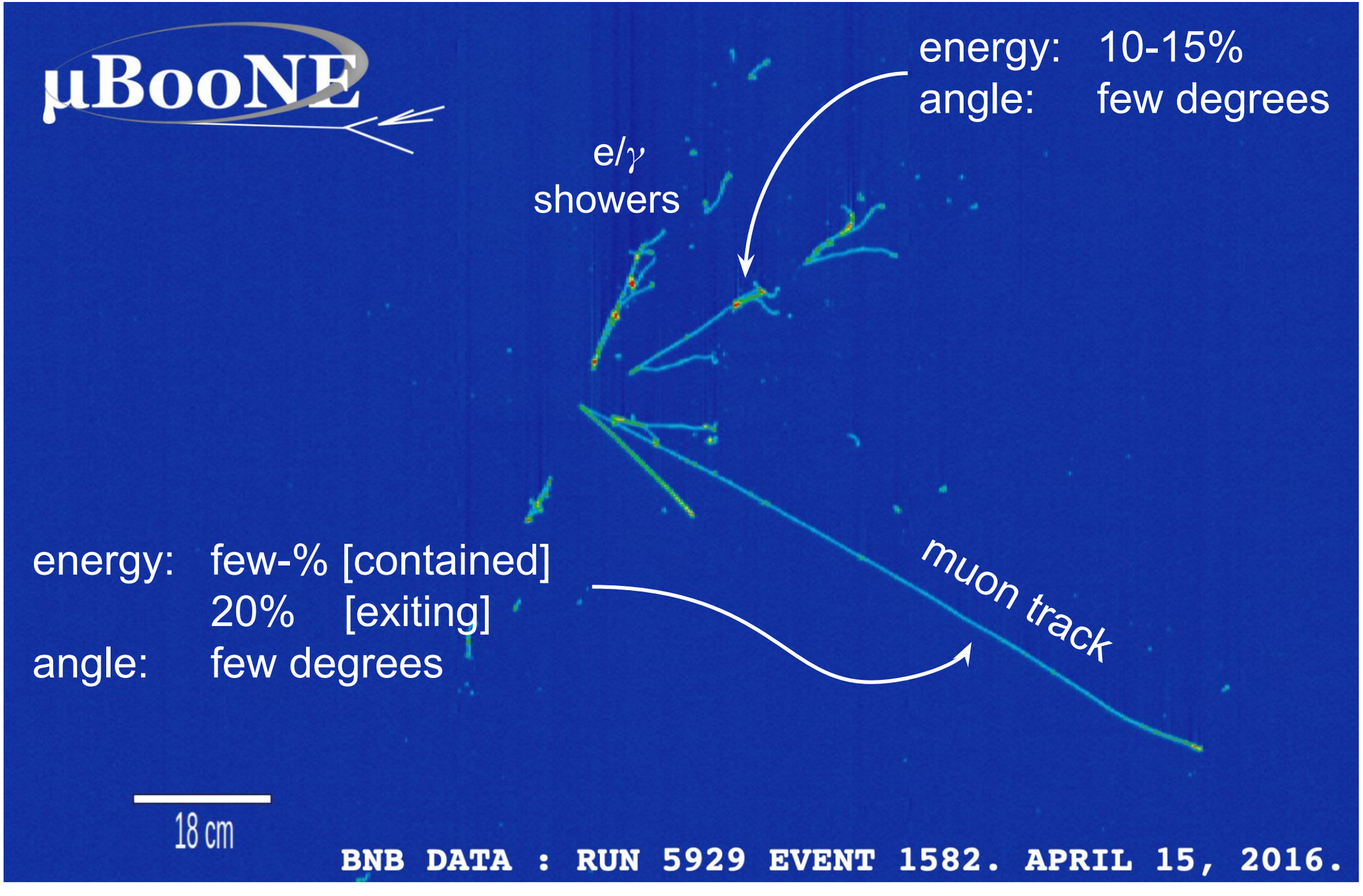
Outline

(1) Why MicroBooNE has an important role to play in neutrino scattering measurements & how we've taken advantage of the LArTPC technology to make our measurements.

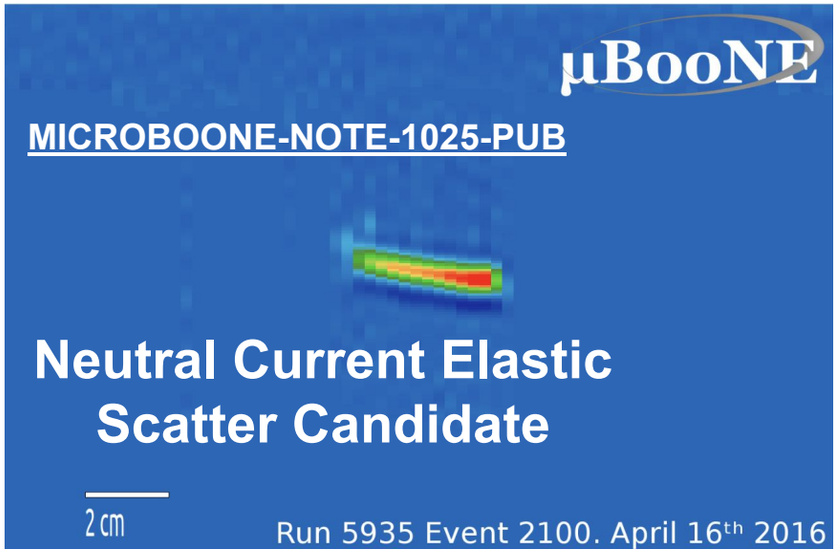
(2) What cross section results we've produced so far and what we've learned from them.

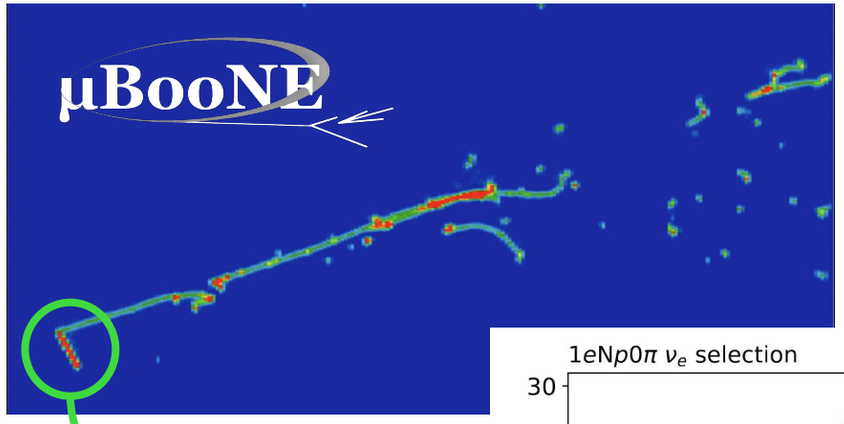
(3) Broader impact and what's next…

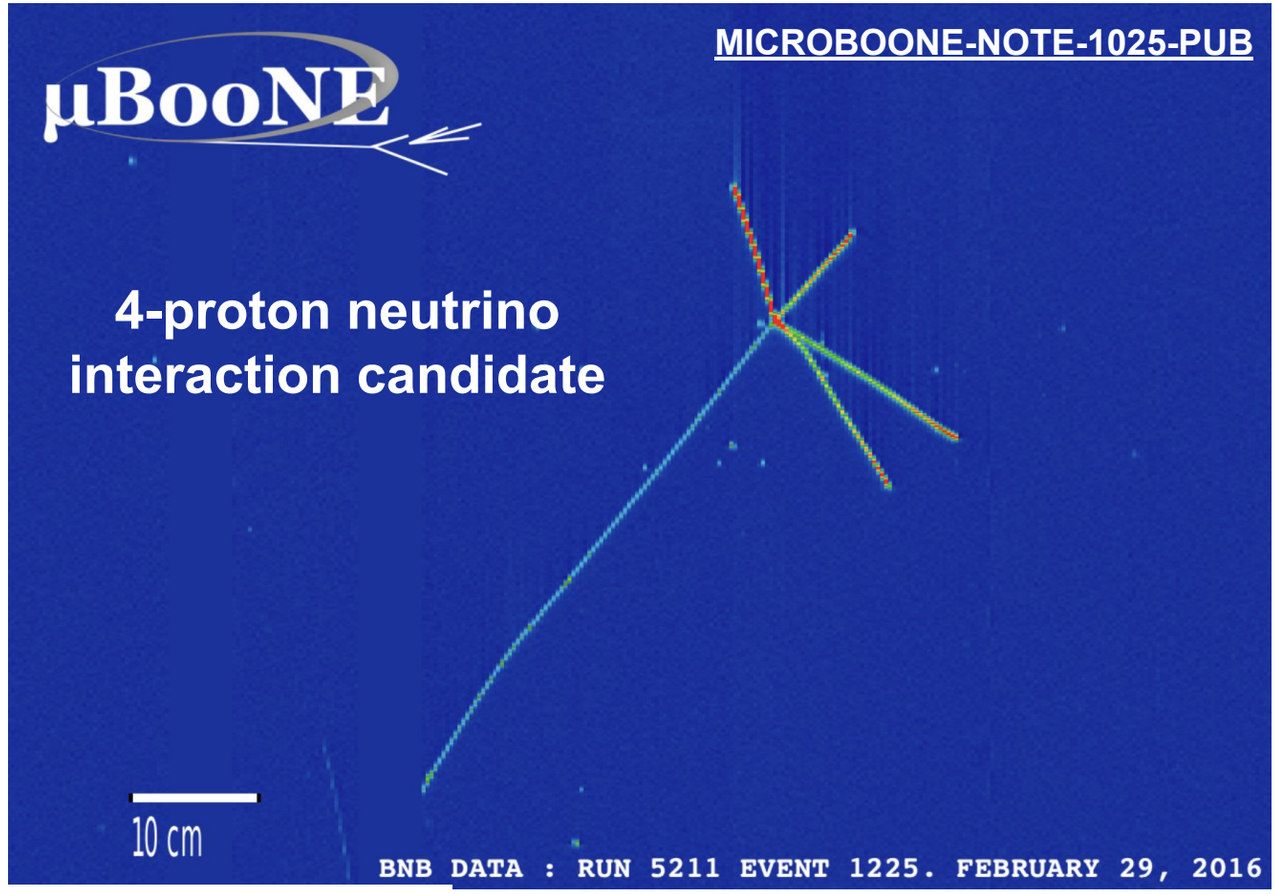
New Landscape for Detector Observables

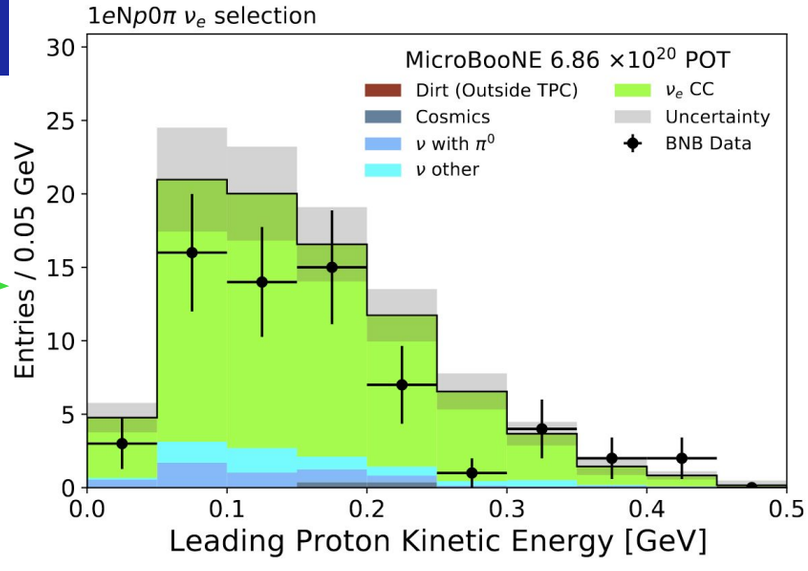


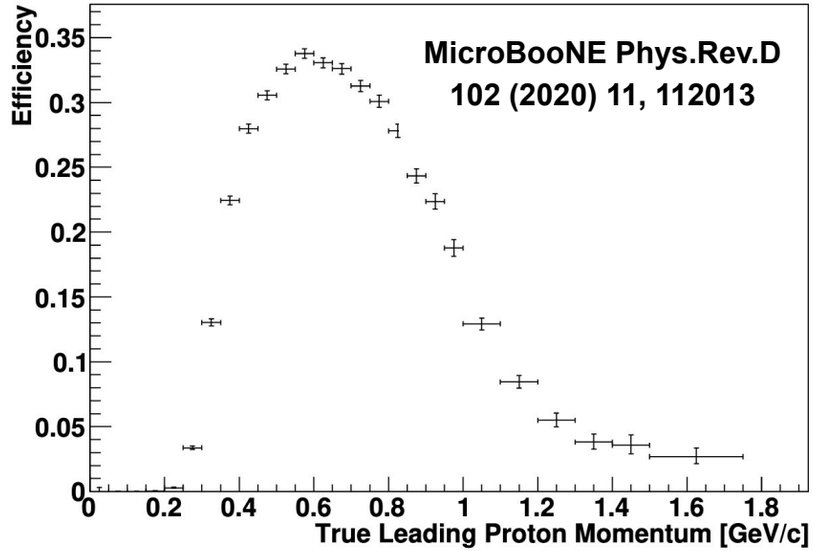
Detector Observables: Protons





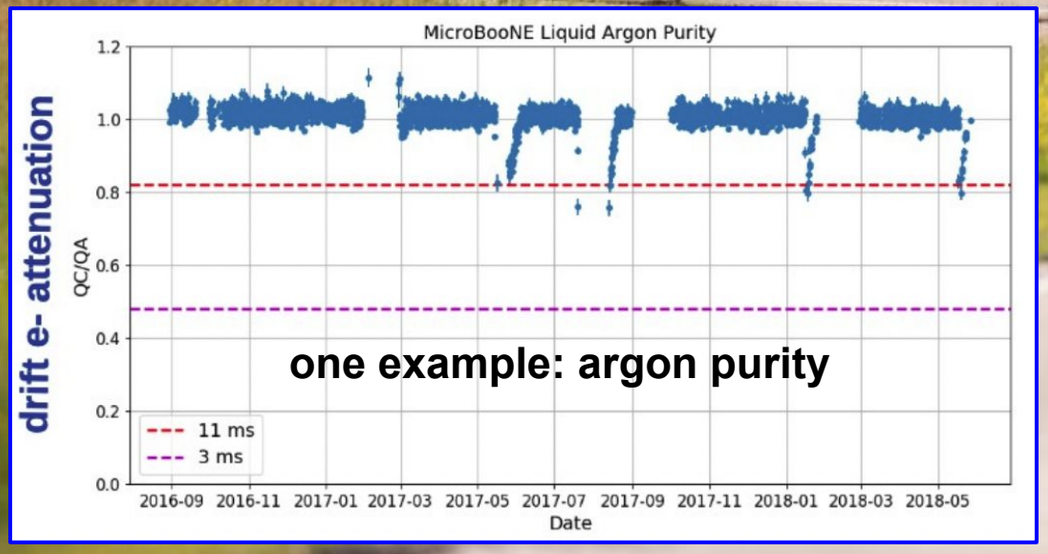


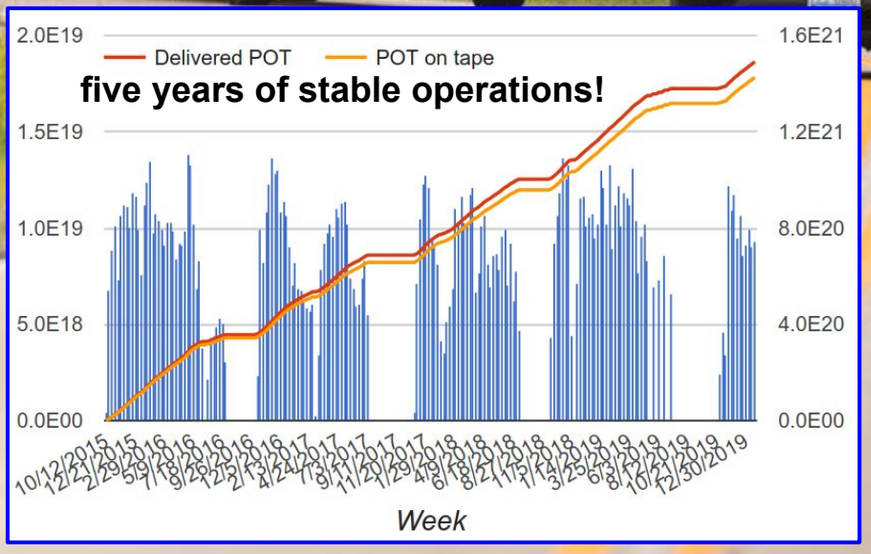




How We Got Here – Detector

summer 2014



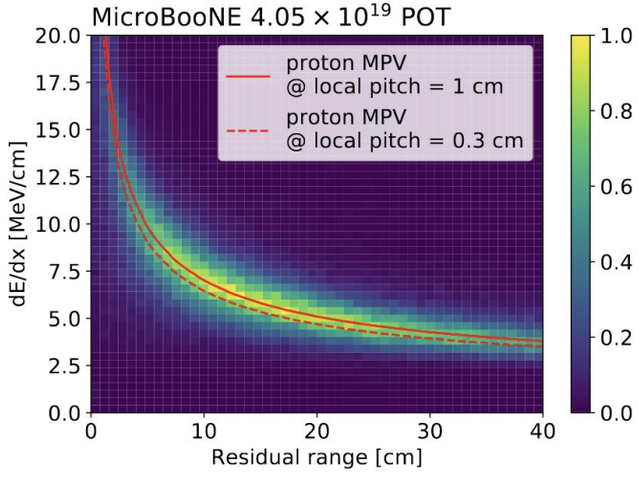


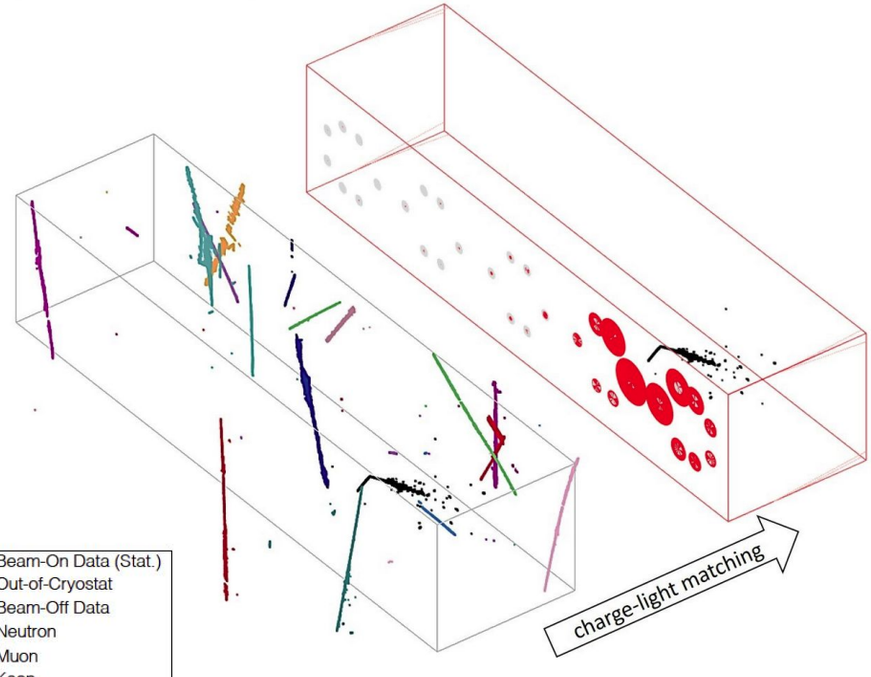
How We Got Here – Analysis

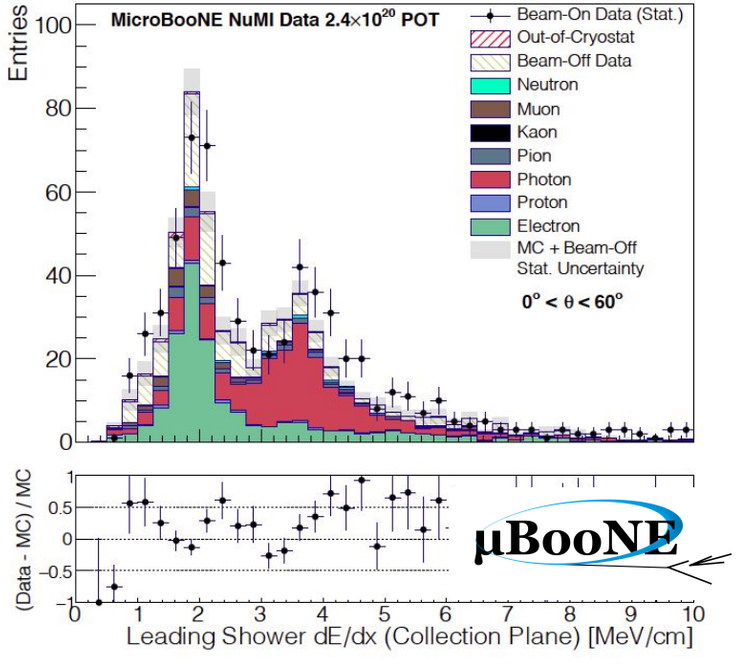
Pioneered many analysis techniques which have enabled the fully-automated reconstruction tools needed for precision measurements, including for its cross-section program.

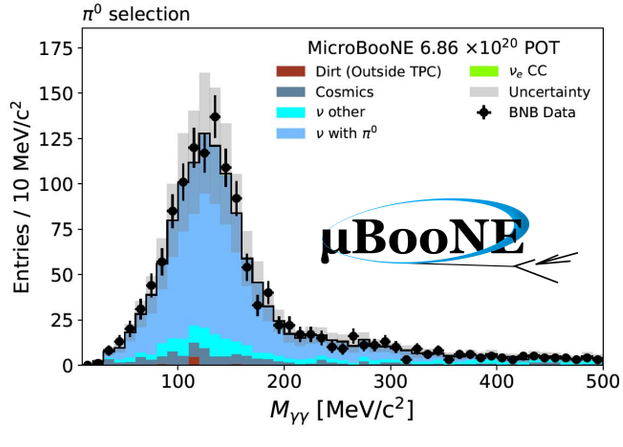
Significant for the broader accelerator-based neutrino program [DUNE,SBN]

JINST 12 (2017) 08, P08003
JINST 12 (2017) 09, P09014
JINST 13 (2018) 07, P07006
JINST 13 (2018) 07, P07007
JINST 15 (2020) 07, P07010
JINST 15 (2020) 12, P12037
JINST 15 (2020) 02, P02007
JINST 15 (2020) 03, P03022
JINST 15 (2020) 12, P12037
JINST 16 (2021) 09, P09025
JINST 16 (2021) 12, T12017
PRD 103 (2021) 9, 092003
JHEP 12 (2021) 153
arXiv:2110.13961 [physics.ins-det]
arXiv:2203.10147 [physics.ins-det]
arXiv:2201.05705 [hep-ex]
arXiv:2111.03556 [hep-ex]





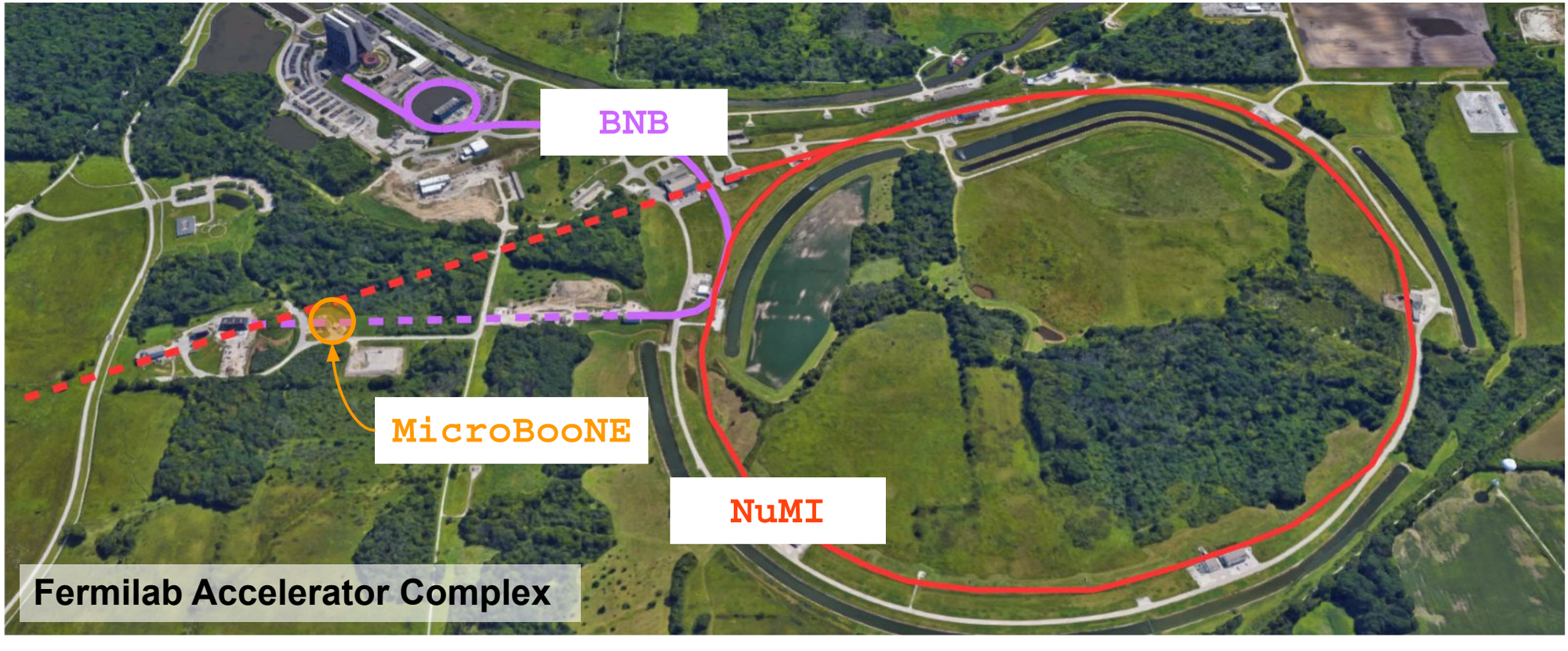




MicroBooNE's Neutrinos

MicroBooNE sits on two neutrino beamlines:

- Booster Neutrino Beamline [BNB]
- Neutrinos at the Main Injector [NuMI]

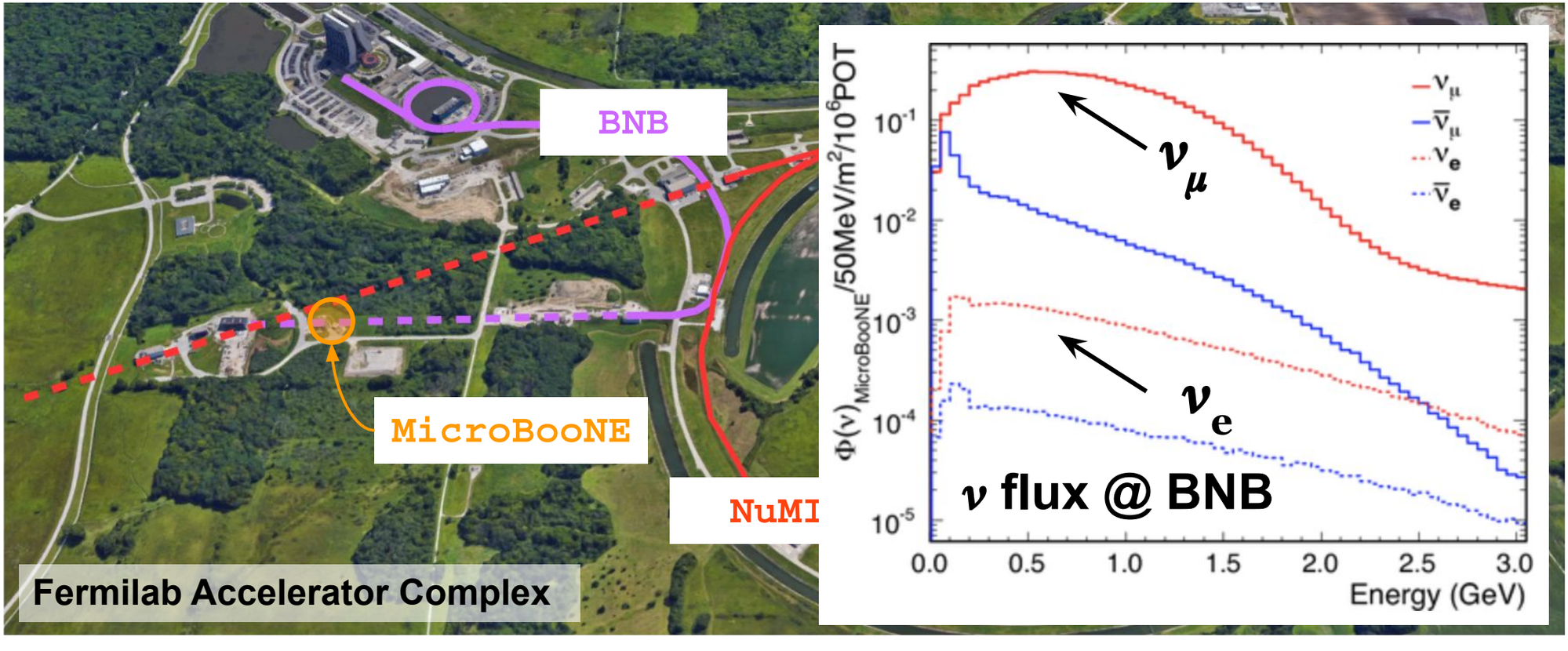


MicroBooNE's Neutrinos : BNB

Booster Neutrino Beamline [BNB]

- On-axis. Mean energy of ~0.8 GeV. 95% ν_μ and < 1% ν_e.
- Collected O(500k) ν_μ neutrino interactions on argon.

Highest stats sample of ν-Ar interactions to date!

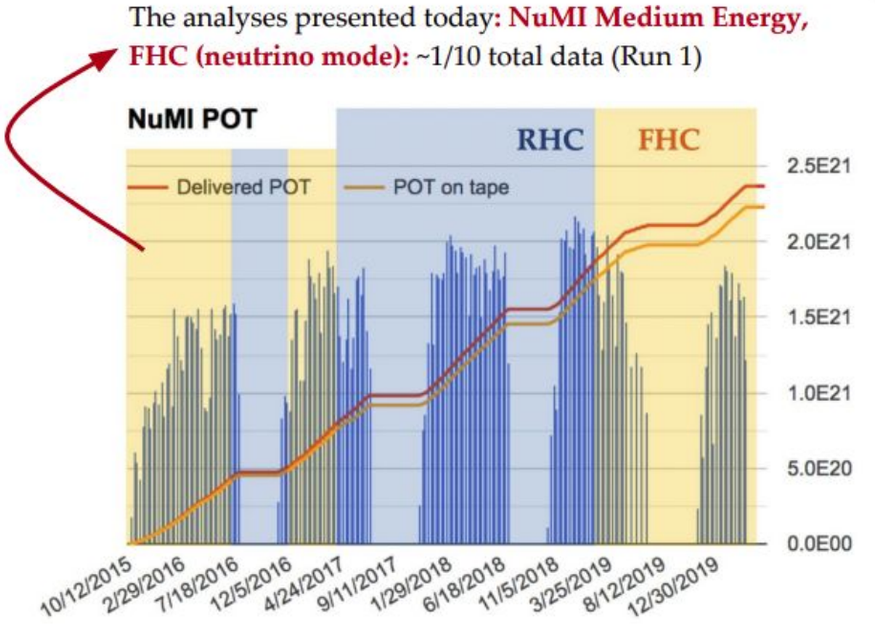


MicroBooNE's Neutrinos : NuMI

NuMI:

- Serves FNAL Long-Baseline oscillation program.
- Off-axis @ MicroBooNE: comparable mean energy as BNB
- Comparable mix of nu / nu-bar
- Lots of electron neutrinos!

NuMI Data Taking

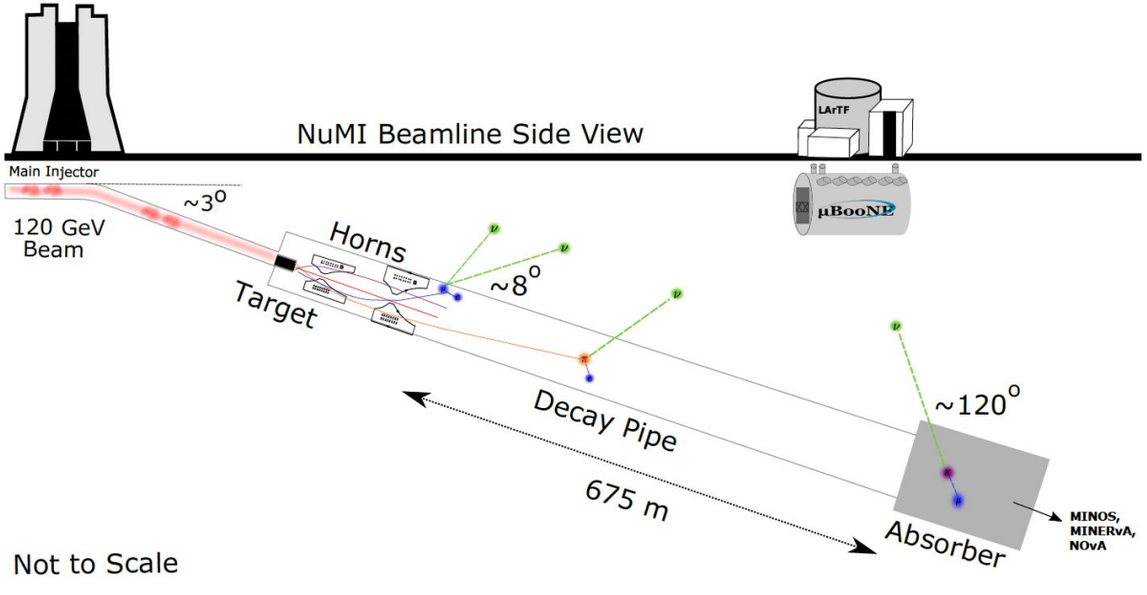


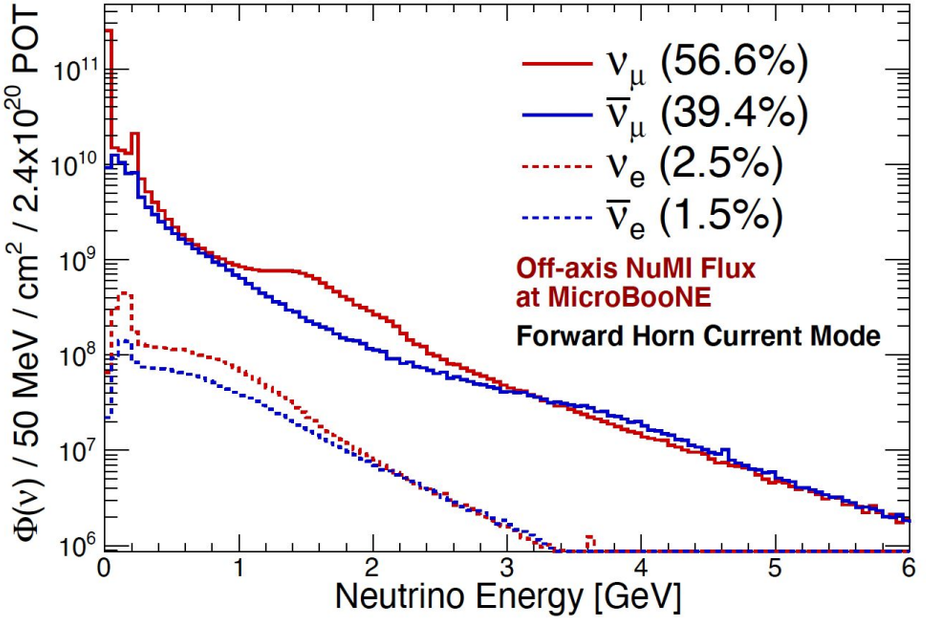
Total NuMI POT on tape:
2.3×10^{21}

Neutrino Mode:
1.0×10^{21}

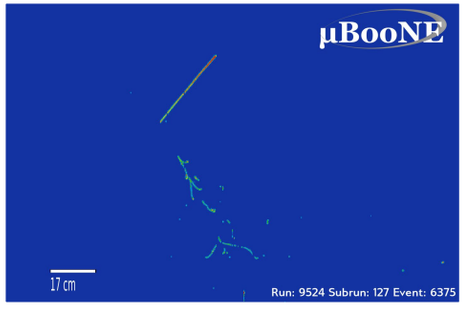
AntiNeutrino Mode:
1.3×10^{21}

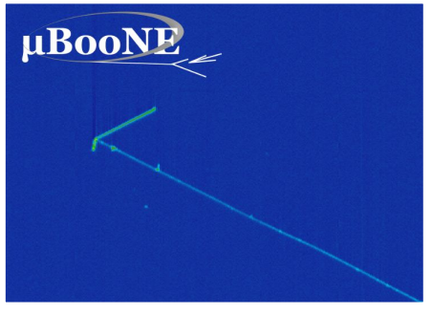
Full dataset:
over 9000 ν_e interactions

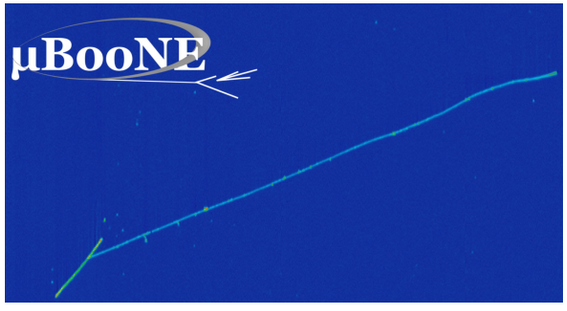


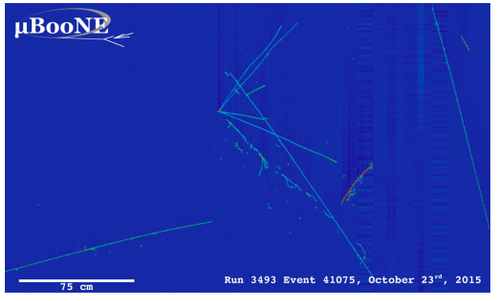


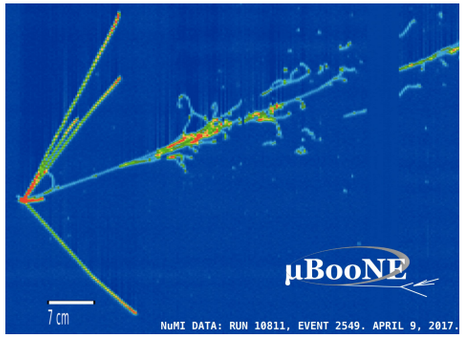
MicroBooNE's Data Set

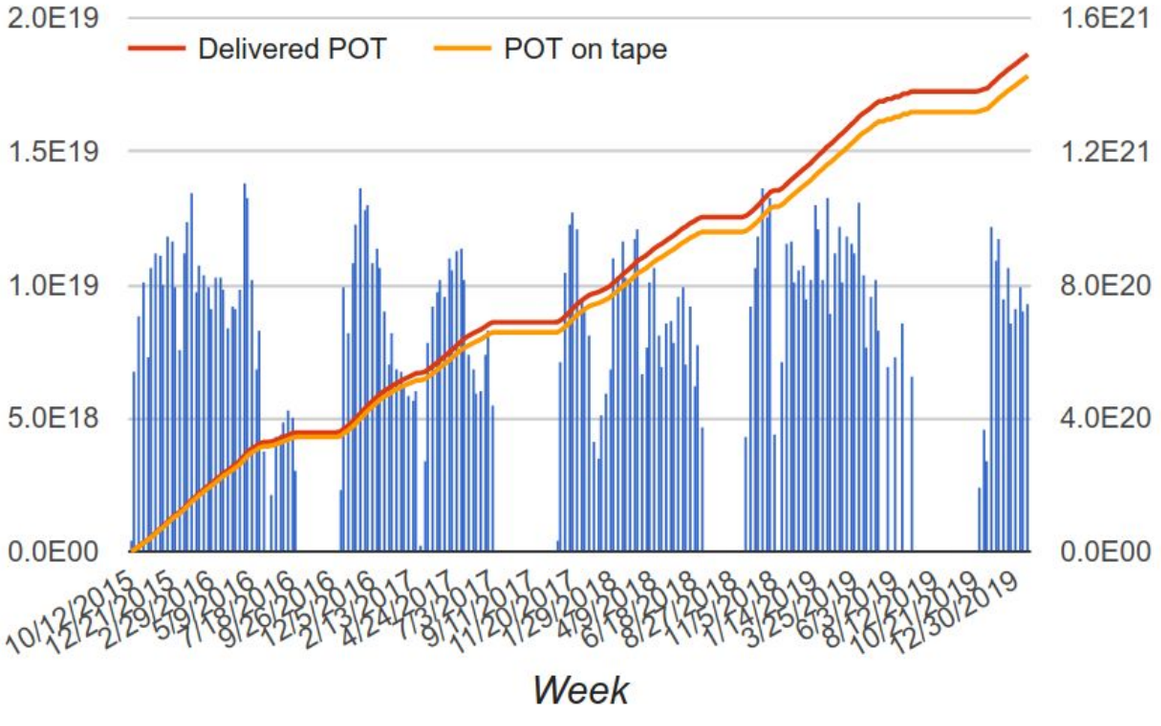


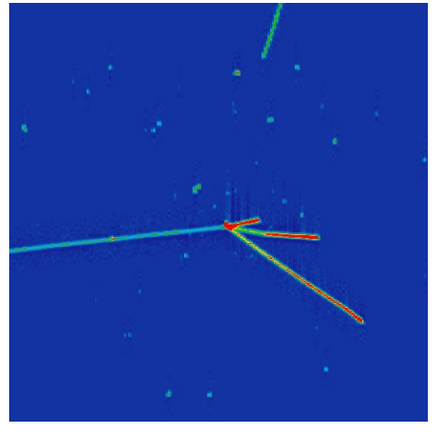


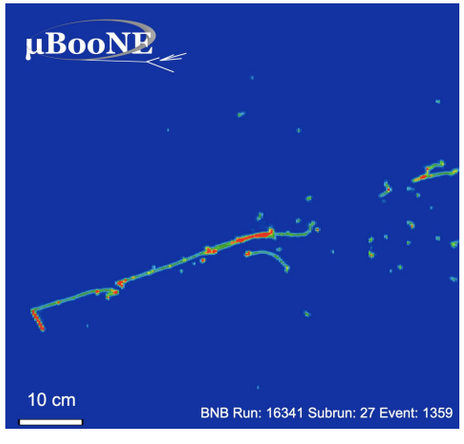


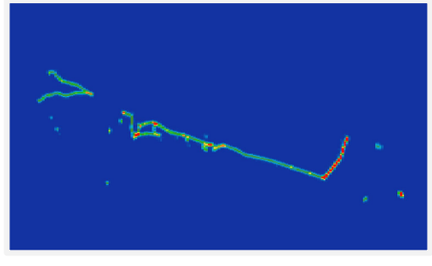


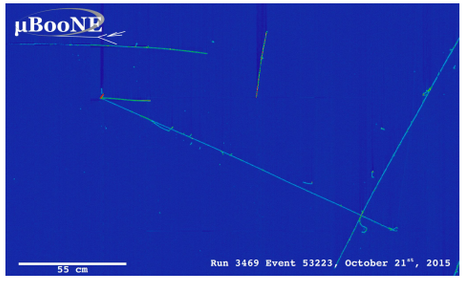




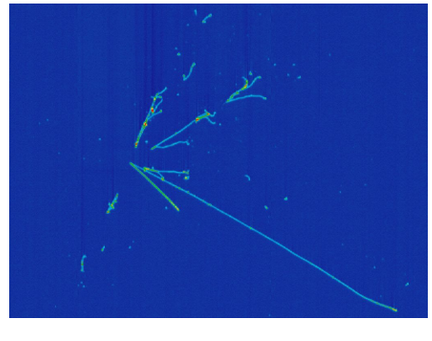




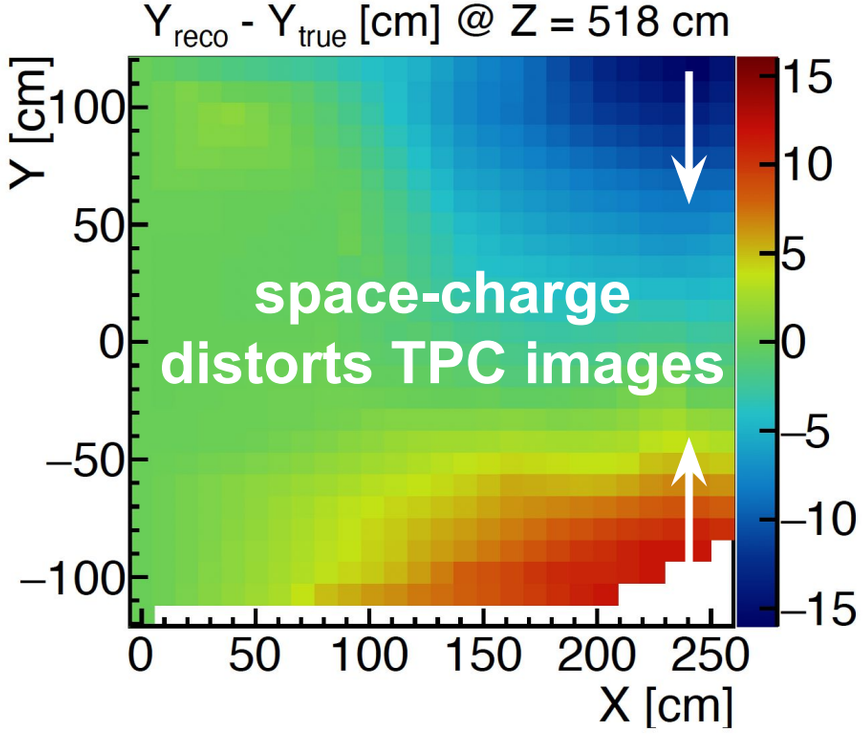


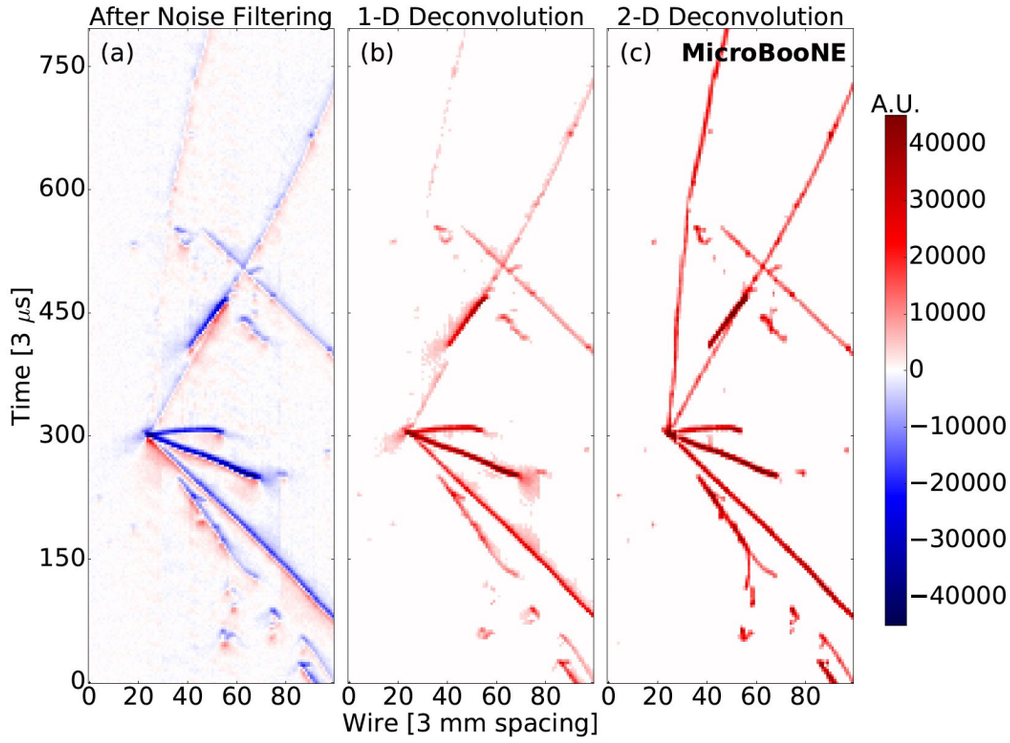


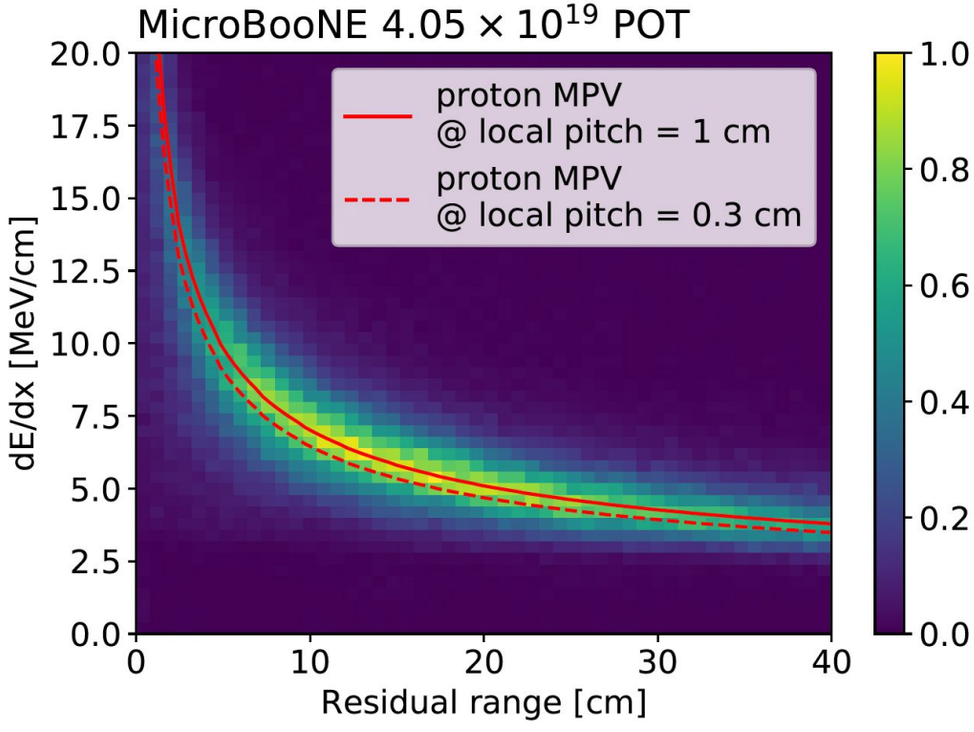
- Longest running large-scale LArTPC to date.
- O(500k) ν interactions collected
- Ramping up high-stats Measurements.

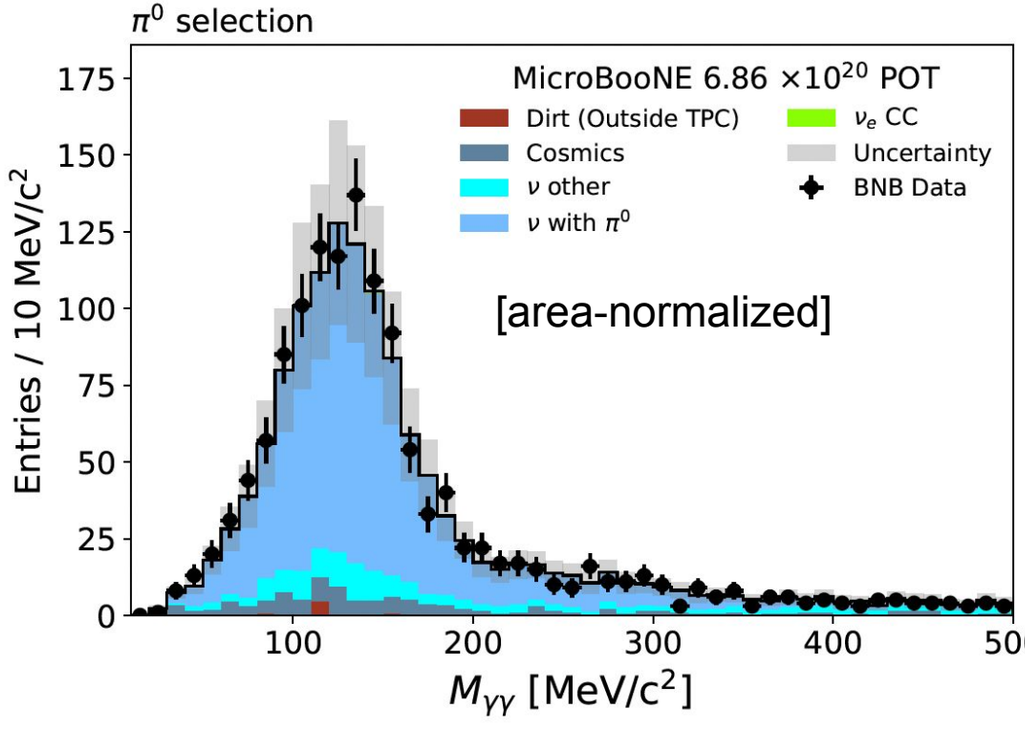


Detector Modeling and Calibrations





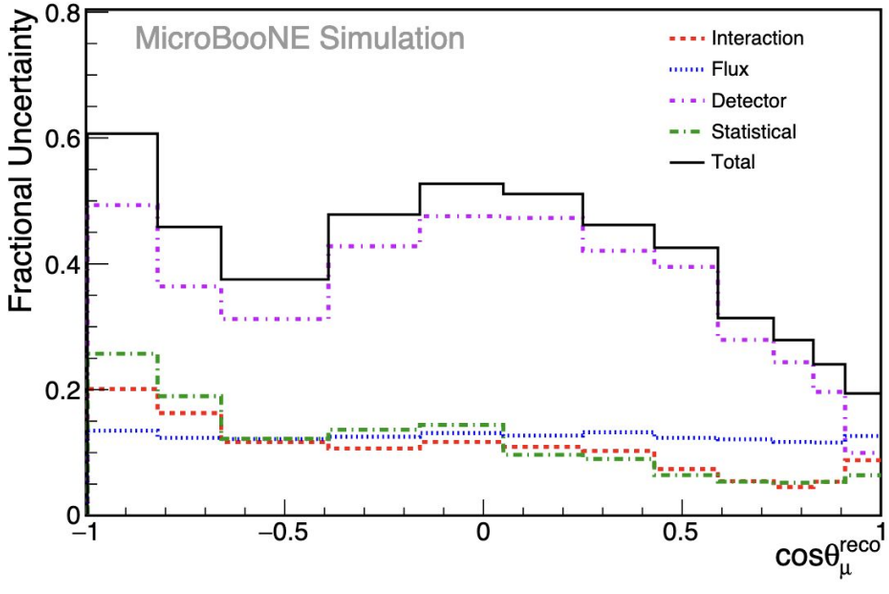


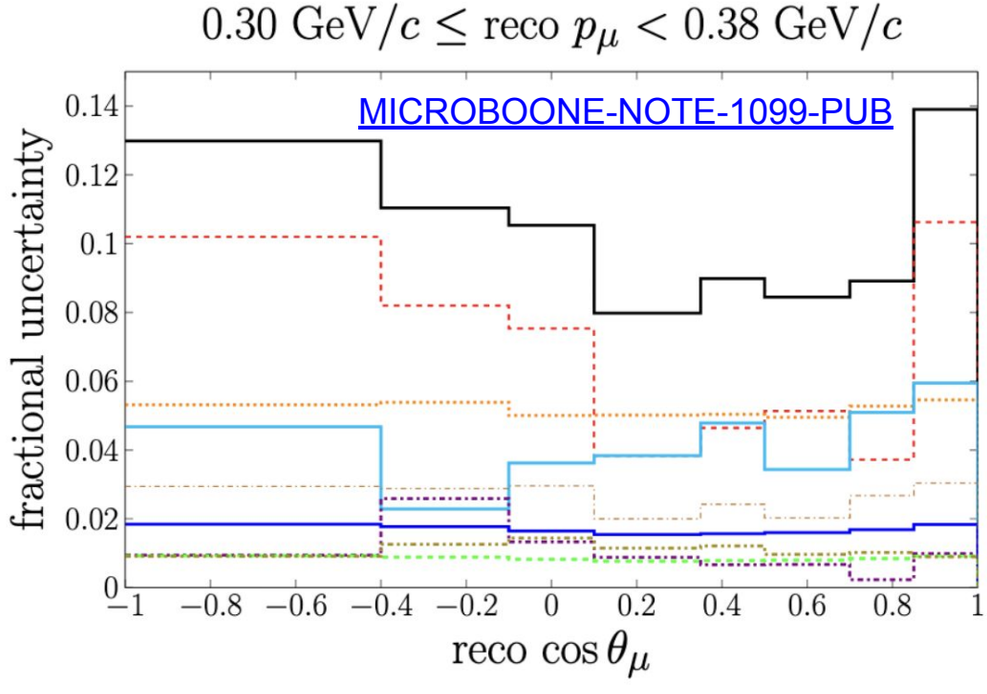


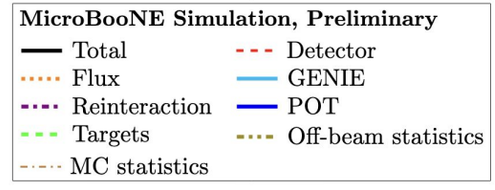
Systematic Uncertainties

Comparison of Systematic uncertainty budget between similar analyses [CC 1μNp0π] with our past [left] and current [right] detector simulation / reconstruction.

Phys.Rev.D 102 (2020) 11, 112013







Big effort to improve detector modeling to reduce impact of systematic uncertainties…

…and in evaluating detector uncertainties: "*Novel Approach for Evaluating Detector-Related Uncertainties in a LArTPC Using MicroBooNE Data*" arXiv:2111.03556 [accepted by EPJC]

Many of our cross-section measurements becoming systematics-dominated, and starting to be dominated by external uncertainties [flux, background cross-sections]

Cross Section Results

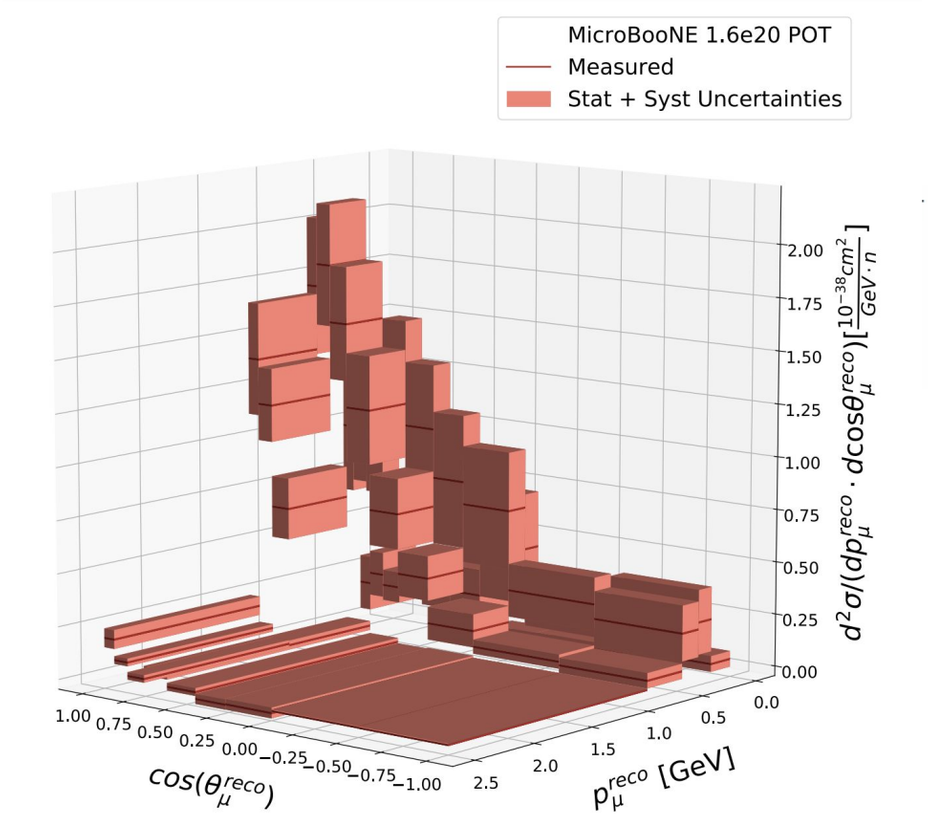
Goals for our Cross-Section Program

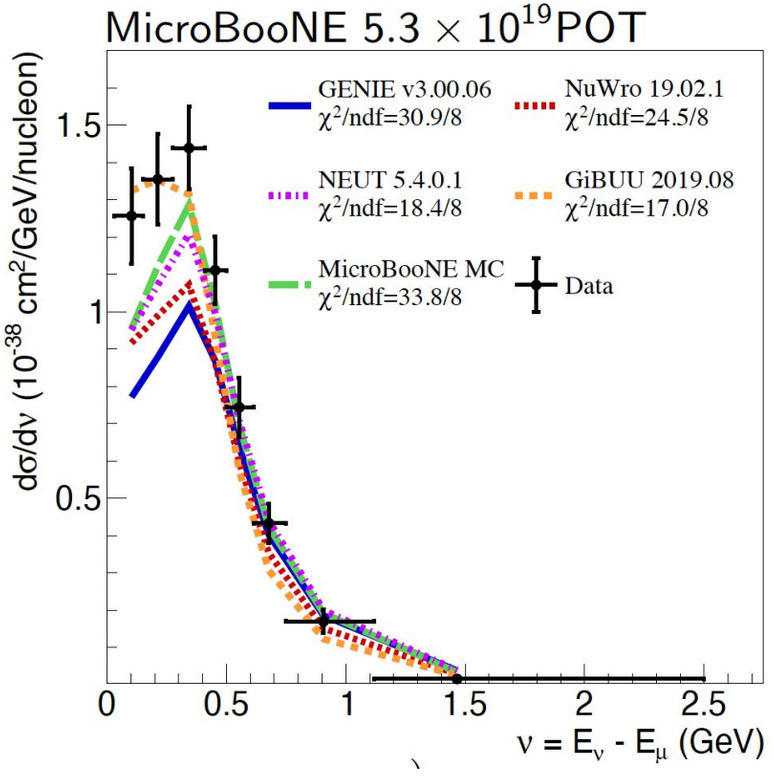
(1) Enrich available measurements of neutrino interactions leveraging the unique capabilities of LArTPC technology, and provide much needed measurements on argon.

(2) Provide comparisons of data with multiple generators + xsec results for external use in an effort to foster development of neutrino interaction modeling and simulation.

(3) Foundation for MicroBooNE's broader physics program searching for BSM physics.

Inclusive Muon Neutrino Cross-Sections





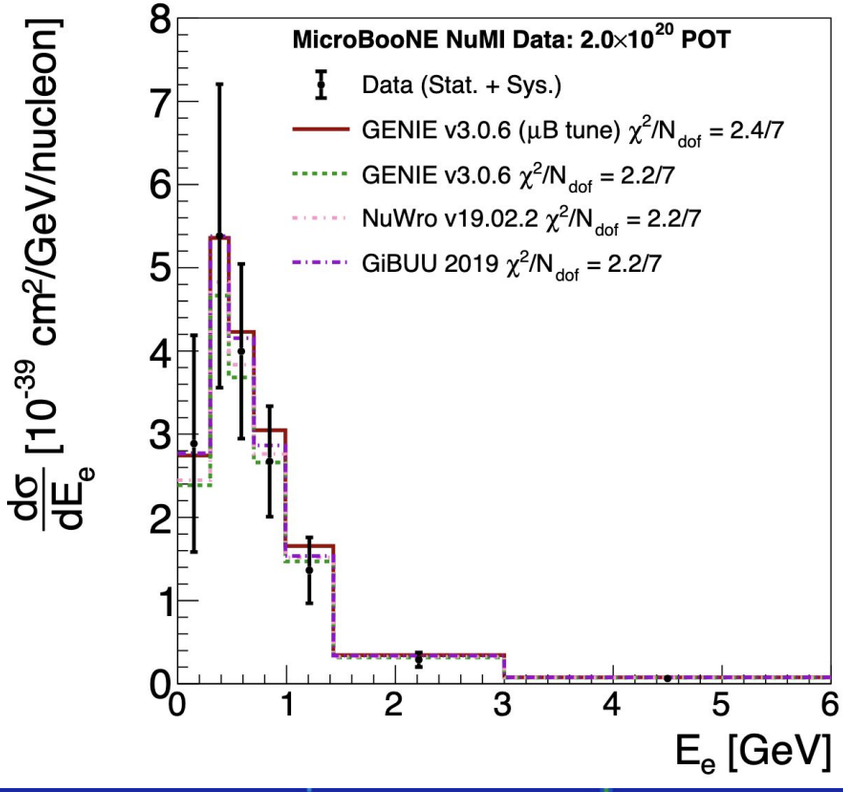
Left: first inclusive cross-section measurement: double-differential in muon kinematics [Phys.Rev.Lett. 123 (2019) 13, 131801]. Highest stats measurement on argon to-date.

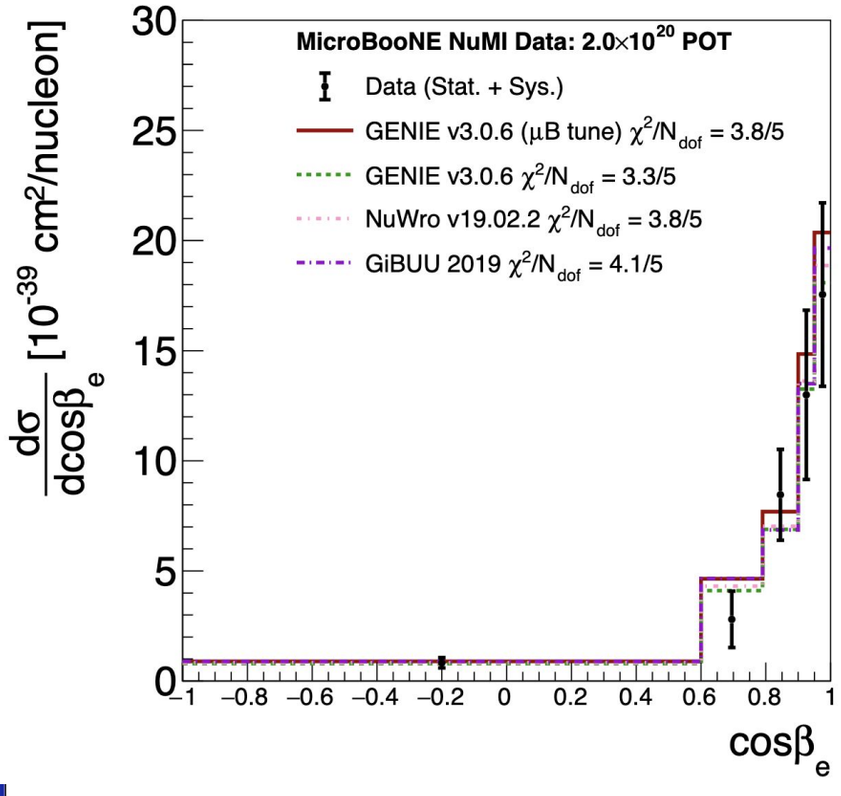
Right [just accepted to PRL] inclusive cross-section looking specifically at hadronic system [arXiv:2110.14023]

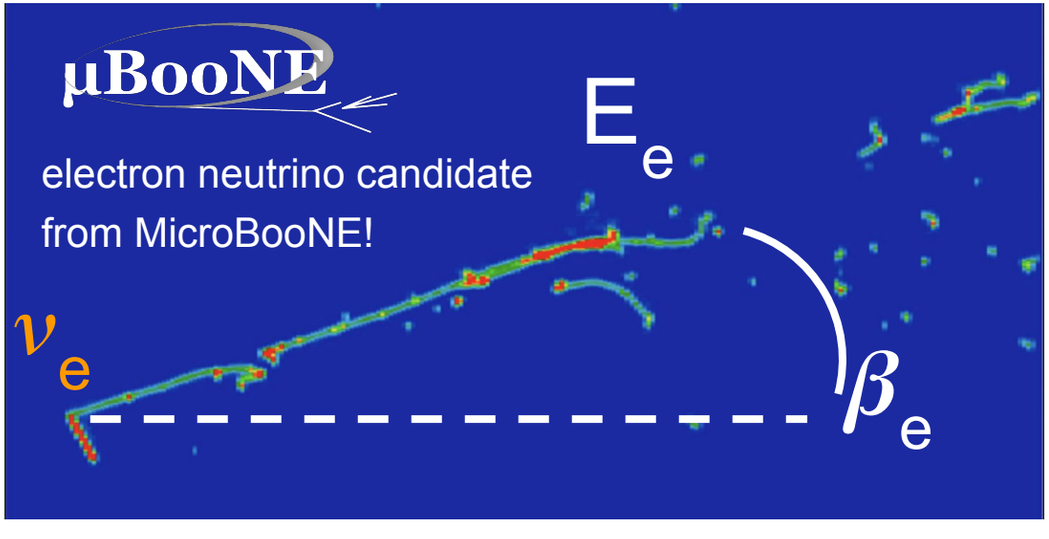
What's next: even higher-statistics, higher-dimensionality measurements.

Inclusive Electron Neutrino Cross-Sections

MicroBooNE, [Phys.Rev.D 105 (2022) 5, L051102]





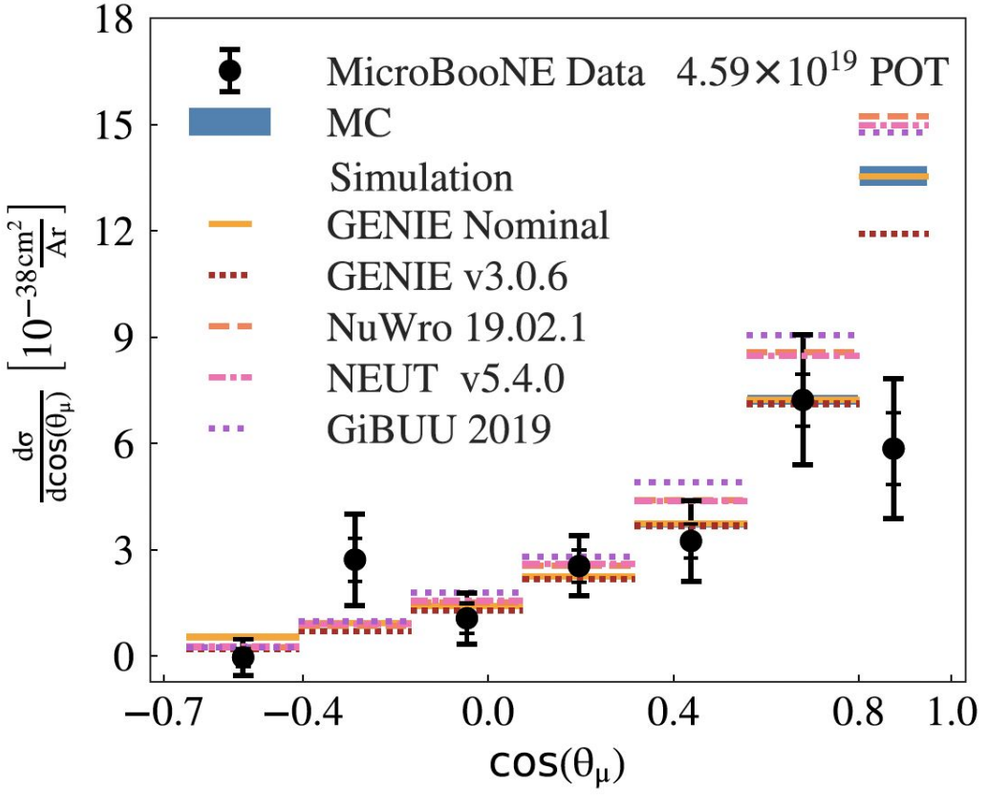


Inclusive measurement shows good agreement with multiple generators.

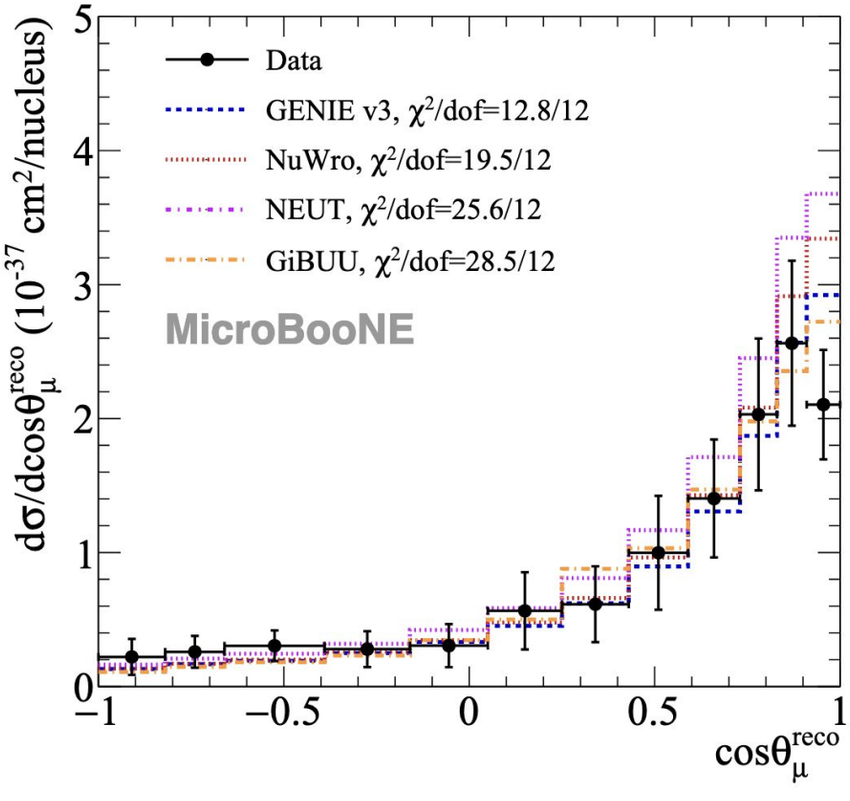
Looking forward to:

- first studies of exclusive final-states.
- Analyses with full ν_e dataset

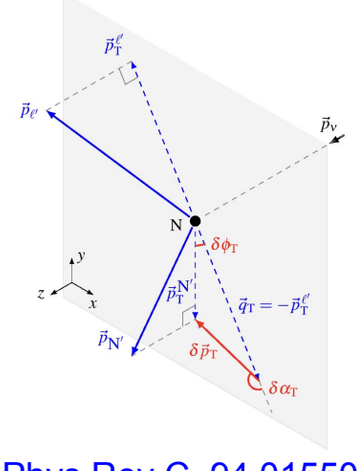
Looking at Exclusive Final-States: Protons



CCQE-like [Phys.Rev.Lett. 125 (2020) 20, 201803]



CC Np 0π [Phys.Rev.D 102 (2020) 11, 112013]



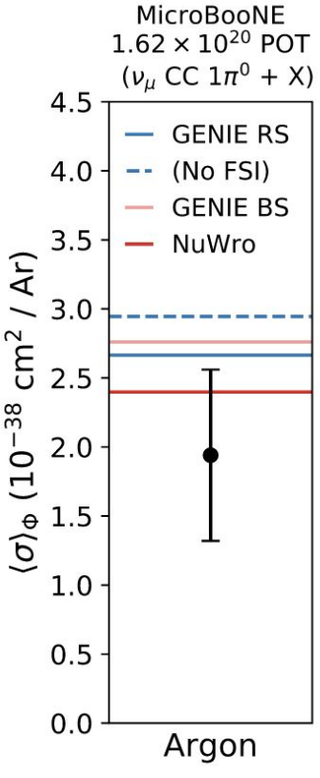
Phys Rev C. 94 015503

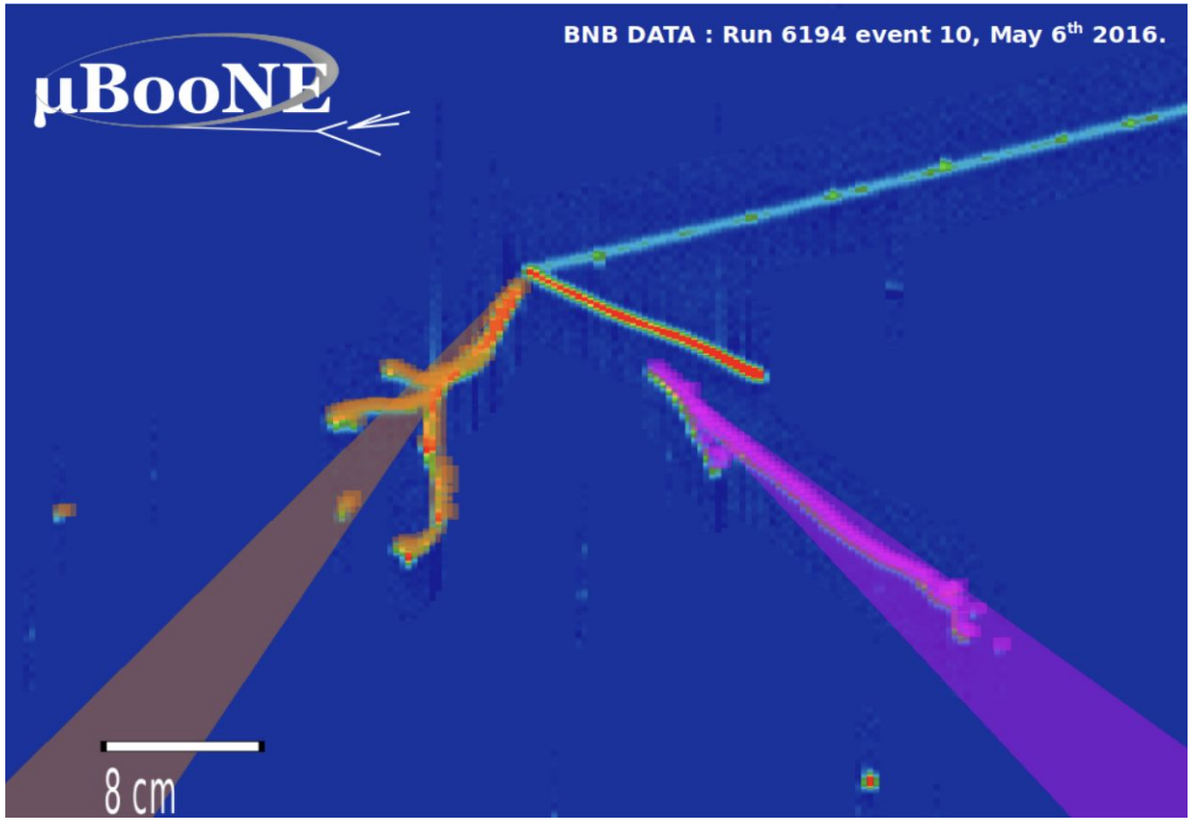
First results looking at exclusive final-states for protons.

Learning a lot about where our models perform well and where they don't.

Moving towards further exclusive final-states and more in-depth look at relevant kinematic variables (e.g. Transverse Kinematic Imbalance) to probe specific impact of different interaction modes and final-state processes.

Looking at Exclusive Final-States : Pions





First flux-integrated cross-section measurement of charged-current pi0 production: [Phys.Rev.D 99 (2019) 9, 091102]

Many mature follow-up analyses which we hope to share results from soon:

1D diff. CC $1\pi^{+/-}$ ***η production*** ***integrated NC π^0*** ***1D diff. CC π^0*** ***1D diff. NC π^0*** ***COH $\pi^{+/-}$***

Resonant pion production important for OSC analyses, both for SBN and DUNE.

Relevant also to MicroBooNE's BSM program probing photon and e^+/e^- final-states.

Broader Impact of Cross-Sections Results & Future Plans

GENIE-tuning Effort

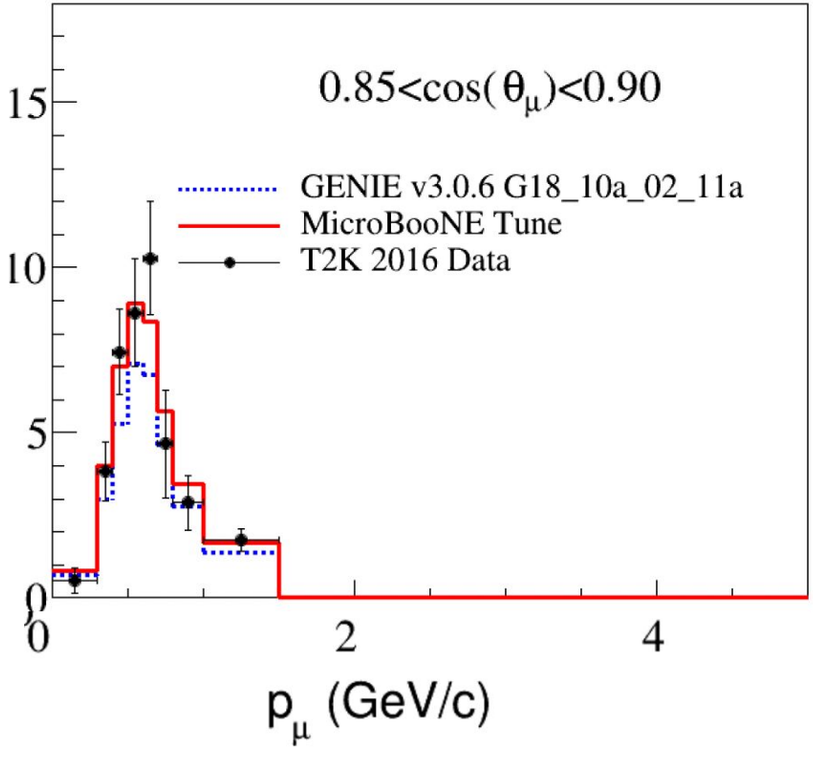
GENIE v3.0.6 “G18_10a_02_11a” for choice of model.

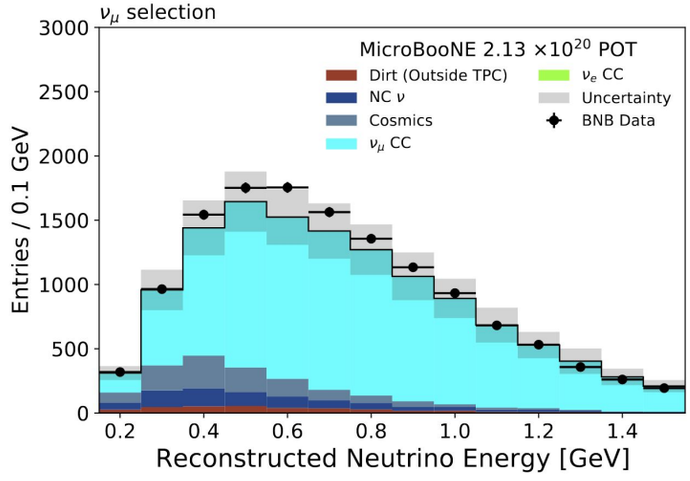
Tuned to external data: T2K CC0π cross-section data.

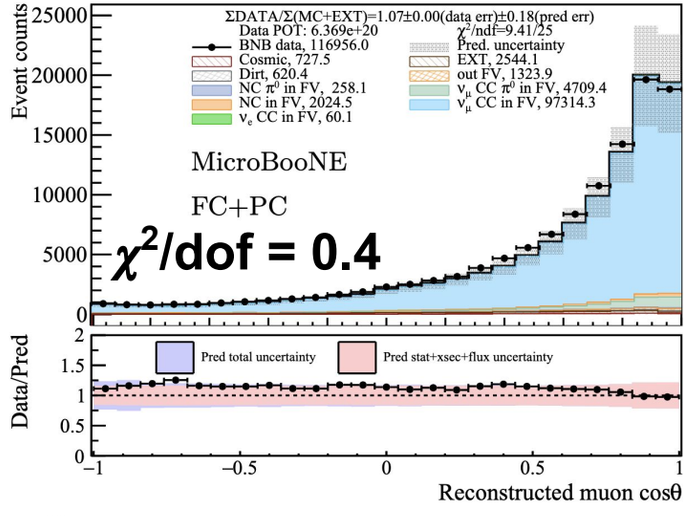
- O(GeV) energy beam, similar flux as BNB

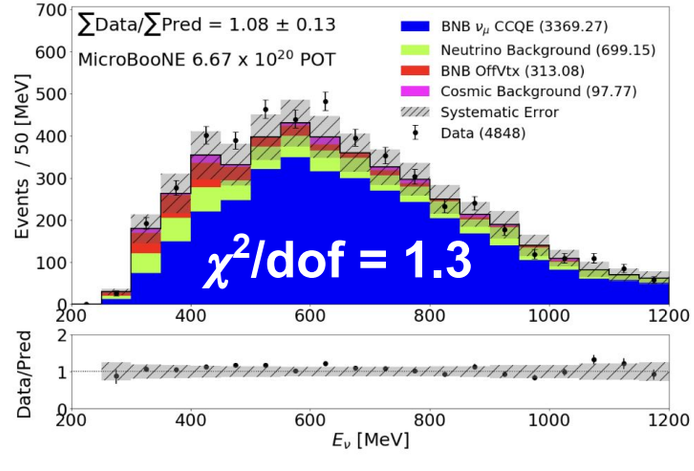
4-parameter fit for CCQE and MEC processes

T2K: [Phys. Rev. D 93, 112012 (2016)]







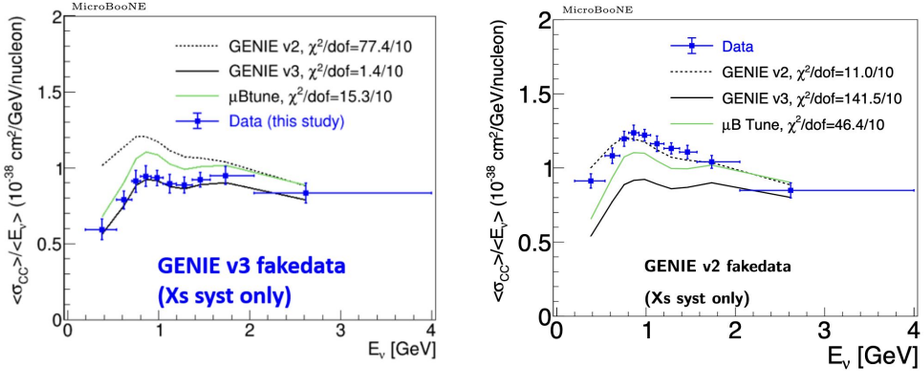


“New Theory-driven GENIE Tune for MicroBooNE”
[accepted to PRD] [arXiv:2110.14028]

Case-Study: Fake-Data Studies and Sidebands

In preparing our Low-Energy-Excess results to investigate the MiniBooNE anomaly took significant time to investigate the robustness of our neutrino interaction model:

1. Eight fake-data sets looking at different model variations:

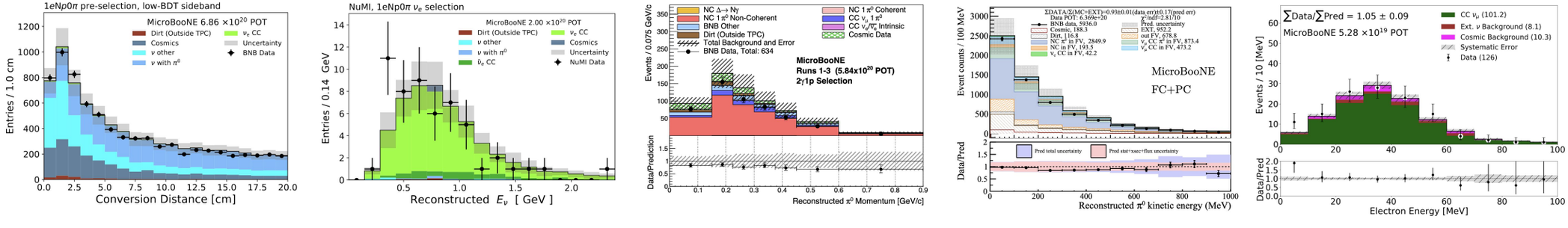


Similar tests performed for Low-Energy-Excess analyses:

- Inject cross-section variation into model.
- Analyzers run analysis blindly.
- Reveal to collaboration if a signal was found or not.
- Discuss…

arXiv:2110.14023, [accepted by PRL] supplemental material

2. Extensive sideband validations.

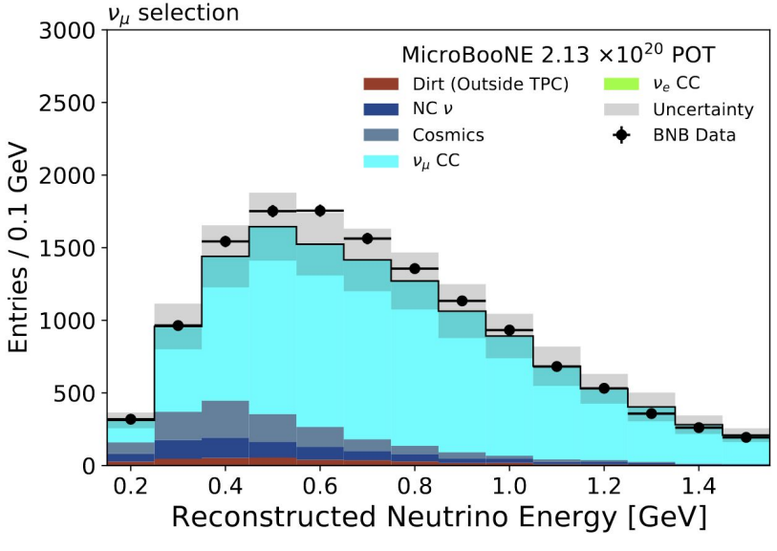


Spent several months focused on these topics. Strong interplay between MicroBooNE's cross-section and BSM programs.

What's Next for MicroBooNE's XSEC

Expect a productive couple of years from MicroBooNE's cross-section program!

- Systematics dominated measurements of different interaction processes in many different final-states.
- Rare process searches.



arXiv:2110.14065 [accepted by PRD]

ν_μ CC $\pi^{+/-}$

ν_μ CC π^0

ν_μ NC π^0

ν_μ 2D CC incl.

ν_μ 3D CC incl.

2D ν_μ CC 0πNp

2D ν_μ CC 0π1p

ν_e CC 0π

NuMI ν_e CC Np

ν_μ CC 0π

NuMI Λ production

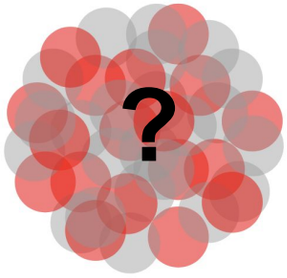
NuMI ν_e / ν_μ

NuMI ν_e-bar

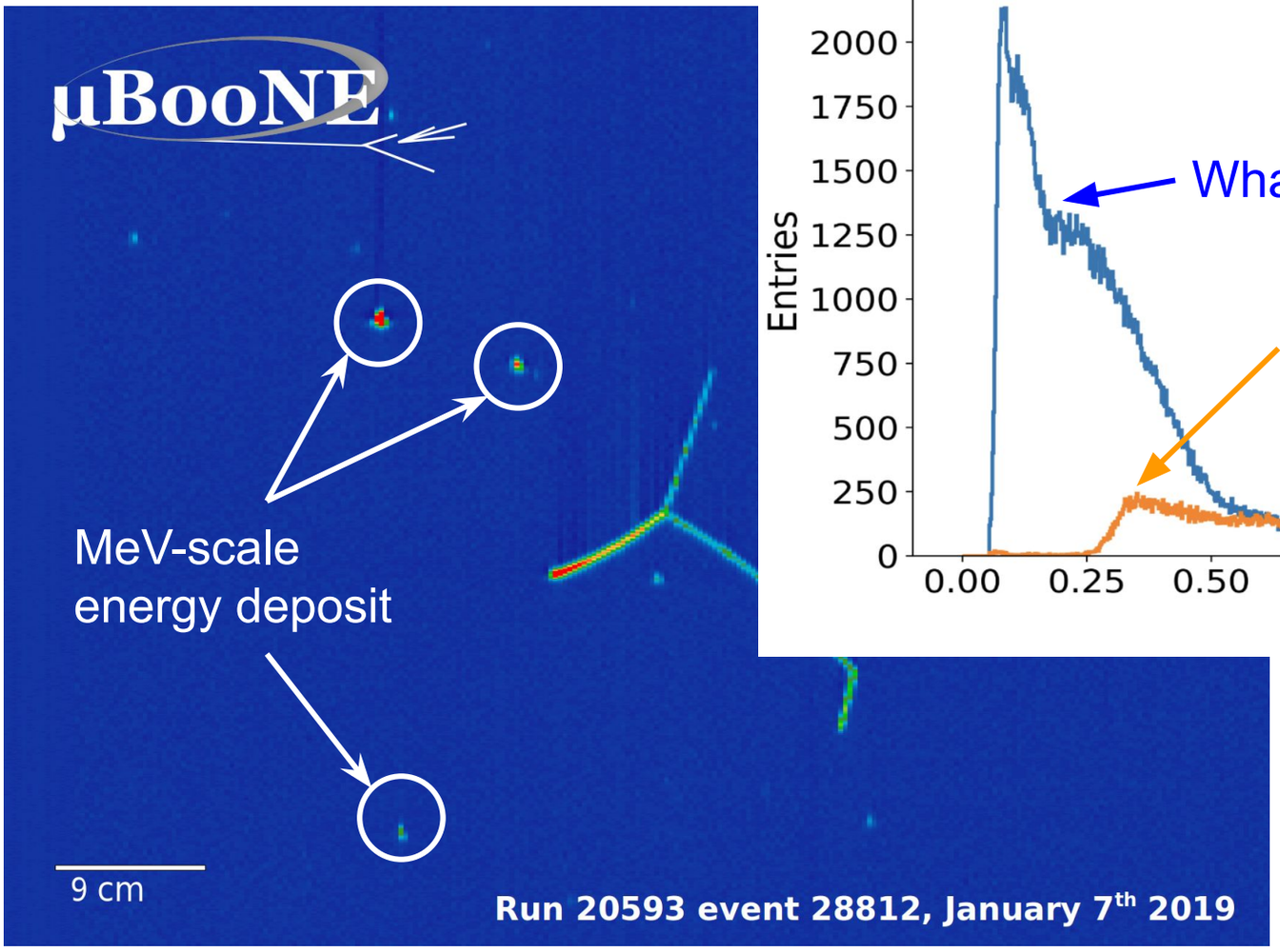
ν_μ CC 2p

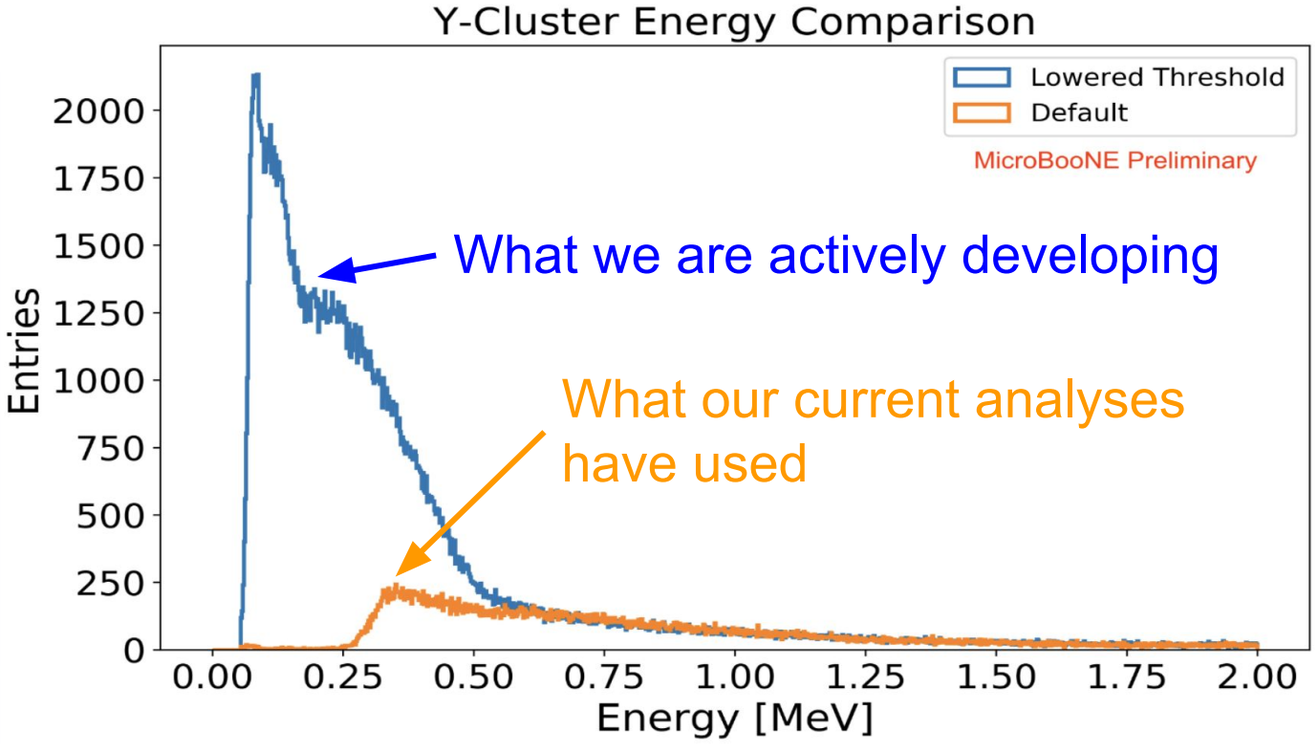
and more…

Next Steps: MeV-Scale Physics



What happens to the nucleus?
- Neutron emission,
- Nuclear de-excitations (γs)

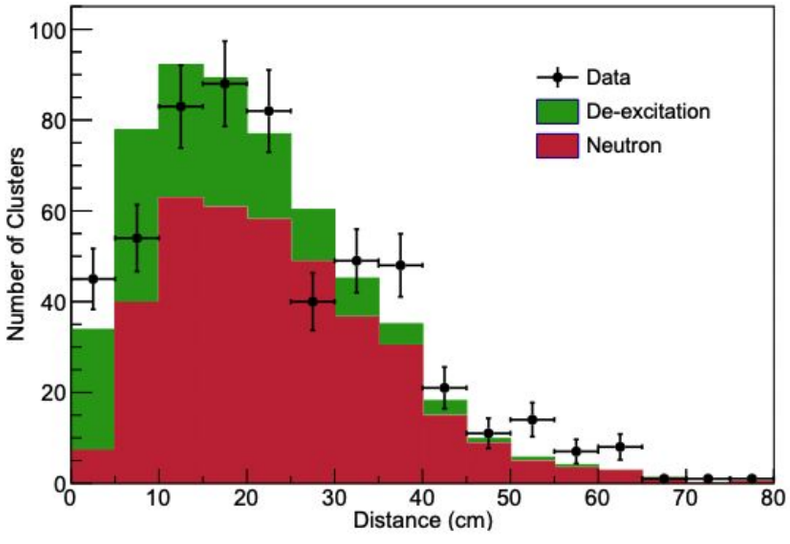




"MeV-Scale Physics in MicroBooNE" - MICROBOONE-NOTE-1076-PUB

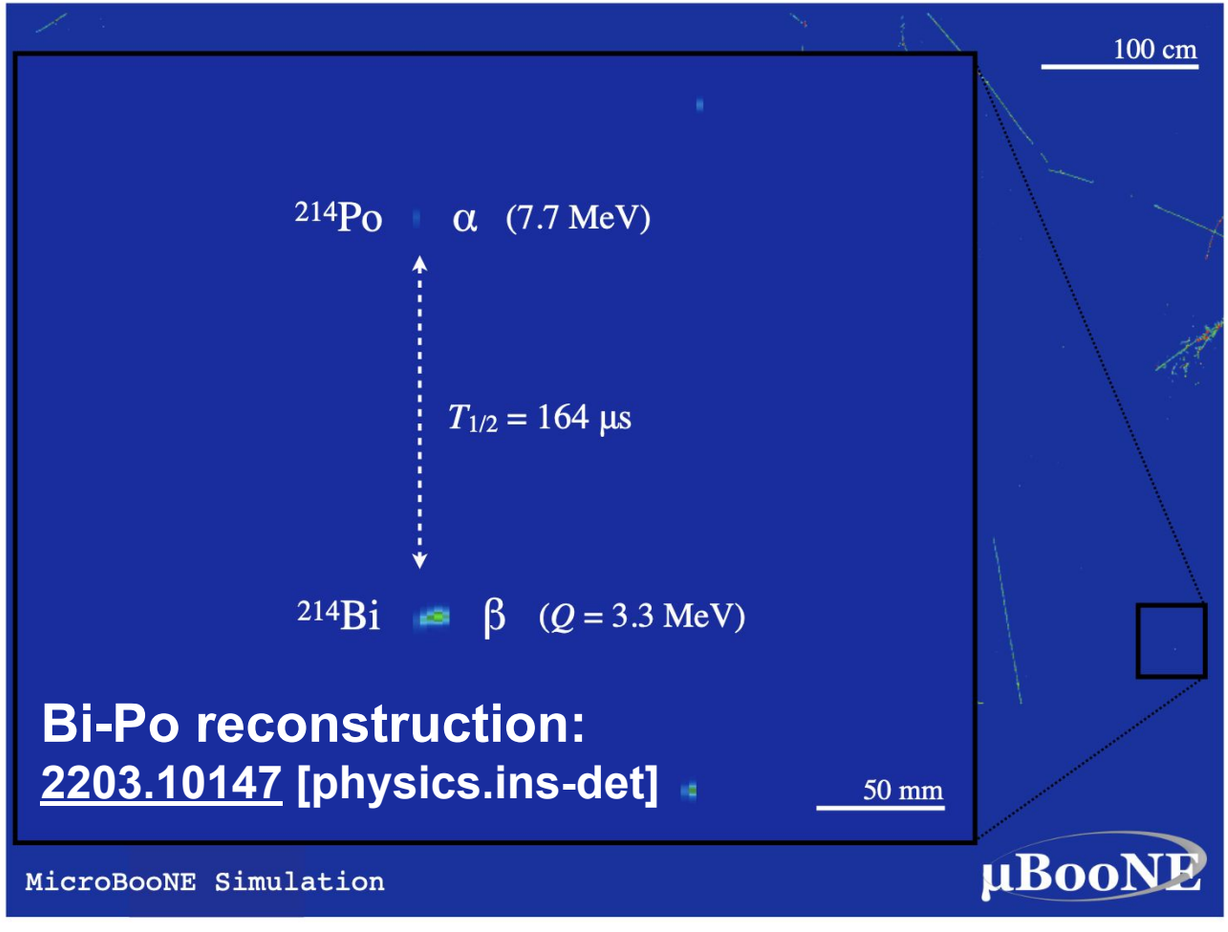
O(100) keV Thresholds!

Next Steps: MeV-Scale Physics



ArgoNeut: Phys. Rev. D 99, 012002 (2019)

Build on first such measurement from ArgoNeuT of MeV-Scale physics in GeV-neutrino interactions.



Why this matters?

"Understanding the Energy Resolution of Liquid Argon Neutrino Detectors", Friedland, Li, Phys. Rev. D 99 (2019) 3, 036009

"Low-Energy Physics in Neutrino LArTPCs", Snowmass White-paper, 2203.00740 [physics.ins-det]

Beyond MicroBooNE

SBND statistics will provide millions of ν-Ar interactions!

"The Short-Baseline Neutrino Program at Fermilab"
Annual Review of Nuclear and Particle Science Volume 69, 2019
Machado, Palamara, Schmitz, pp 363-387

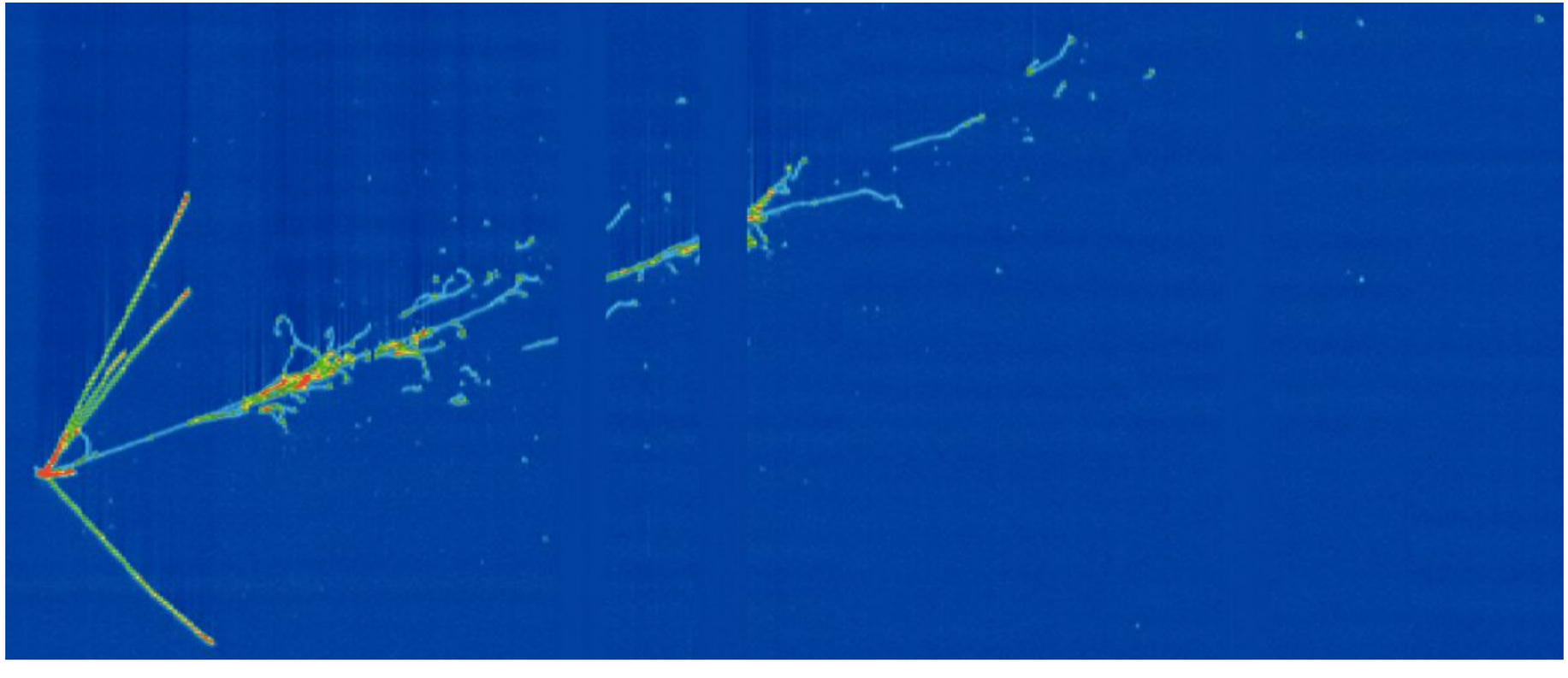
SBND's
- rare-processes
- SBND-PRISM
- low-thresholds for charge & light!

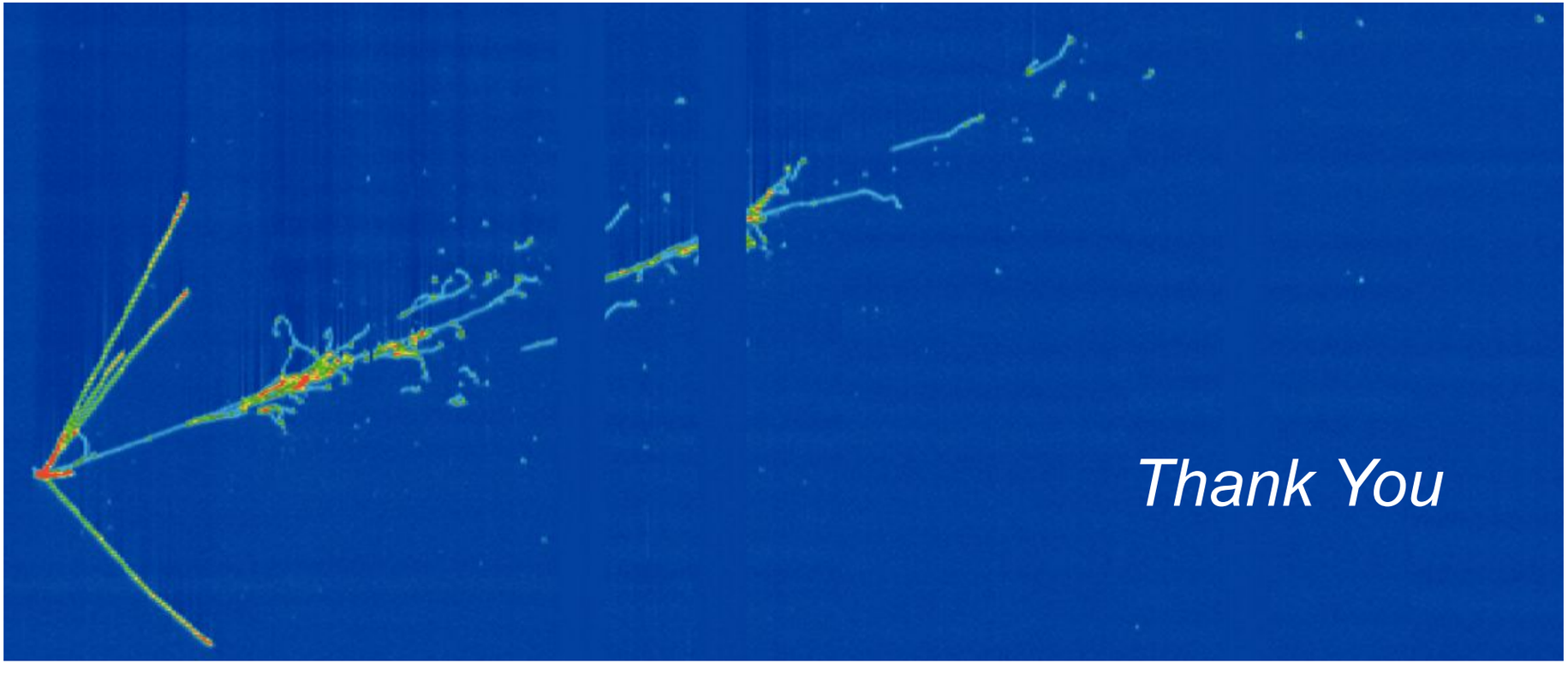
Conclusions

MicroBooNE has a rich neutrino interaction physics program. Many results already published, many more in the pipeline.

Outwards-looking: inform community and provide data with which to benchmark and develop theories/generators.

Inwards-looking: critical to our own broader physics goals and BSM searches in particular.




Thank You