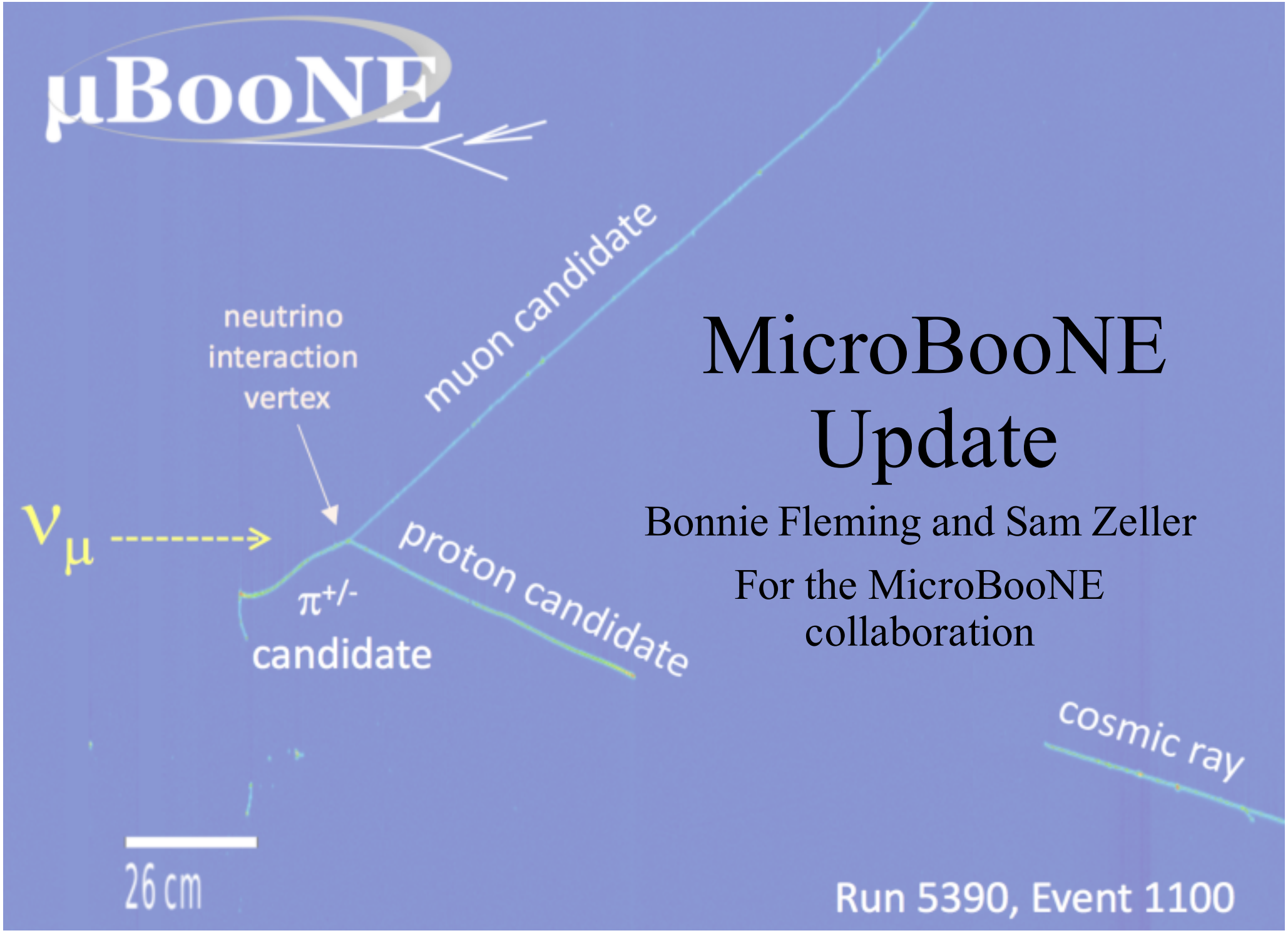



# MicroBooNE Update

Bonnie Fleming and Sam Zeller

For the MicroBooNE collaboration

*From PAC presentation in fall 2017*

# Conclusions

- MicroBooNE has established a strong track record of maintaining stable operations *(95% uptime over past 2 years of running)* and being able to get results out of this detector *(19 public notes; 7 papers: 2 since the July PAC, 8 more in the pipeline).*

  *Now: 25 public notes, 10 papers*

  - A high priority goal is to produce our first neutrino cross section publication(s) in 2018.

    *Three new results and more coming…*

- To date, we have collected a total of $6.57 \times 10^{20}$ POT ($6.25 \times 10^{20}$ POT on-tape), $1 \times 10^{20}$ POT of which includes the cosmic ray tagger. Expect to get to a total of $(8\text{-}9) \times 10^{20}$ POT by summer 2018.

  *Now: 9.6E20 pot delivered: 40% with CRT*

- We remain on an ambitious path for producing new results at summer 2018 conferences. These plans are unchanged from the July PAC, but we are concerned about how long it will take to produce the data and MC samples needed to advance these analyses. Task force is studying this.

  *Solved: See PGS talk for MicroBooNE Computing Model*

# Interaction and Cross Section Measurements in publication and preparation for submission

- Charged Particle Multiplicity
- CC $\nu_\mu$ inclusive
- CC$\pi^0$

Measurements in progress

- NC1p
- CC0$\pi$
  - CC1p
  - CC2p
  - CCNp
- CC$\pi$+
- NuMI $\nu_e$

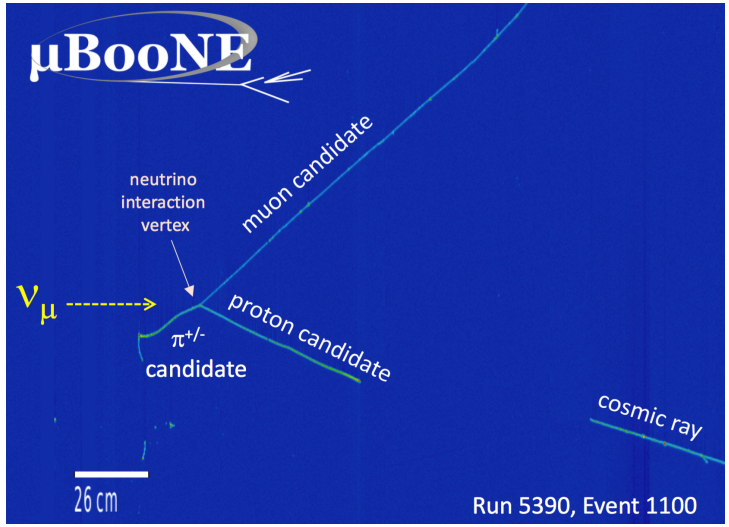
"Physics R&D" (what we pass on to the community...)

- Signal processing
- Uncontained muons
- Cosmic removal techniques
- Proton ID
- Shower reconstruction
- …

Relevant for osc analysis:

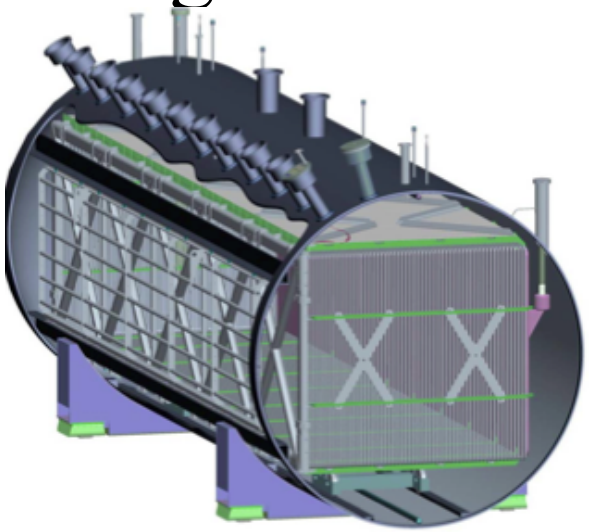
- Data constraints
- Development of reconstruction techniques
- Analysis validation in general

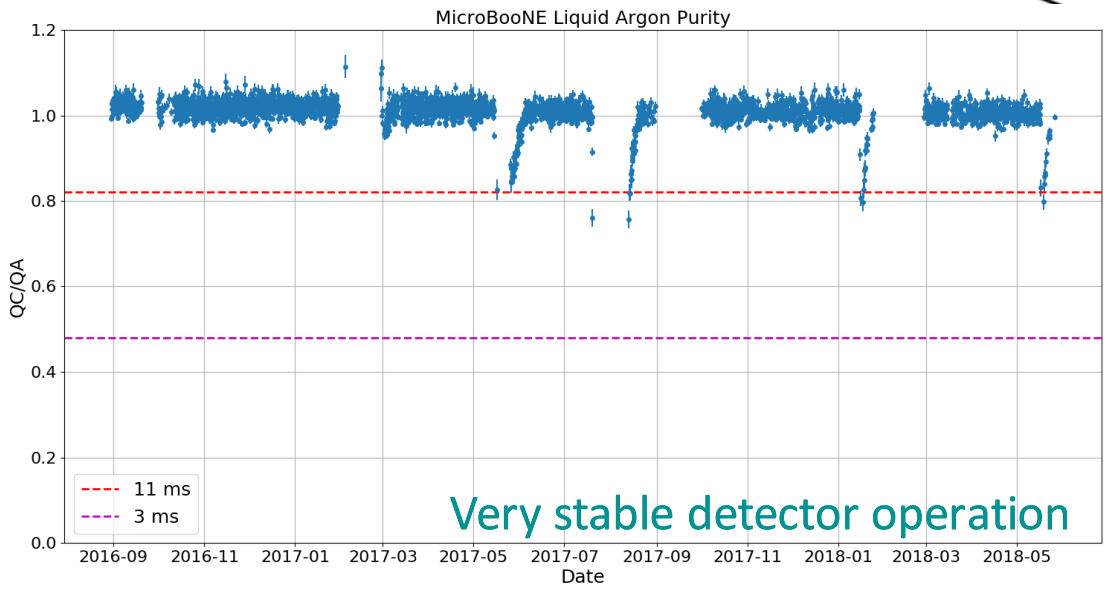
→ Important foundation for oscillation analysis!




*How do we do this?*

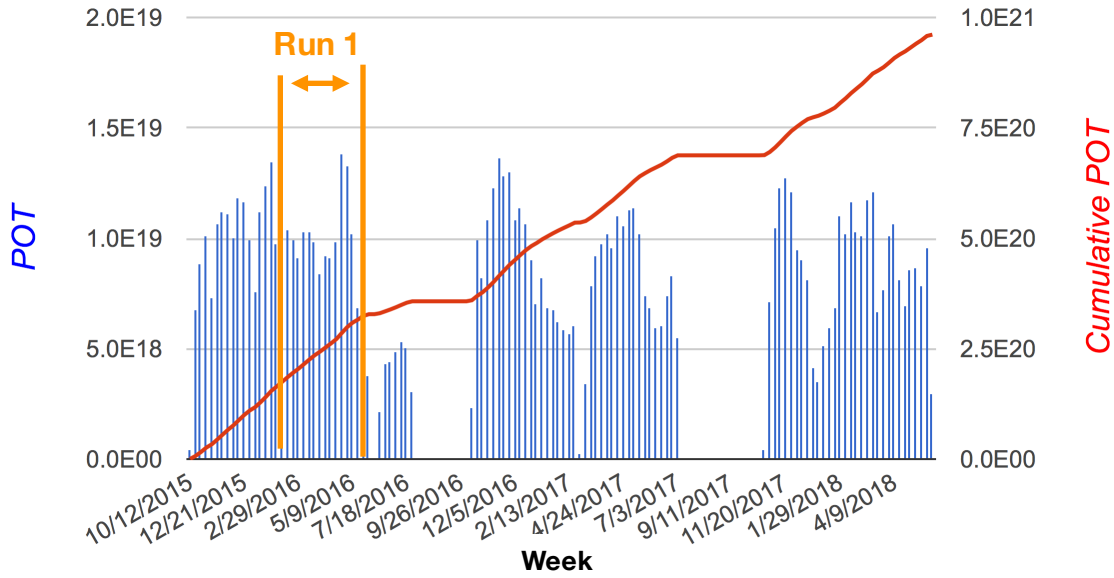
# Taking the data…






- All data open for low level checks
- Run 1 data: samples open for analysis
  - 5 x$10^{19}$ pot open data sample
  - All Run 1 (3.6 x $10^{20}$ POT) for topologies that do not impact blindness for oscillation analysis (ie: CC)

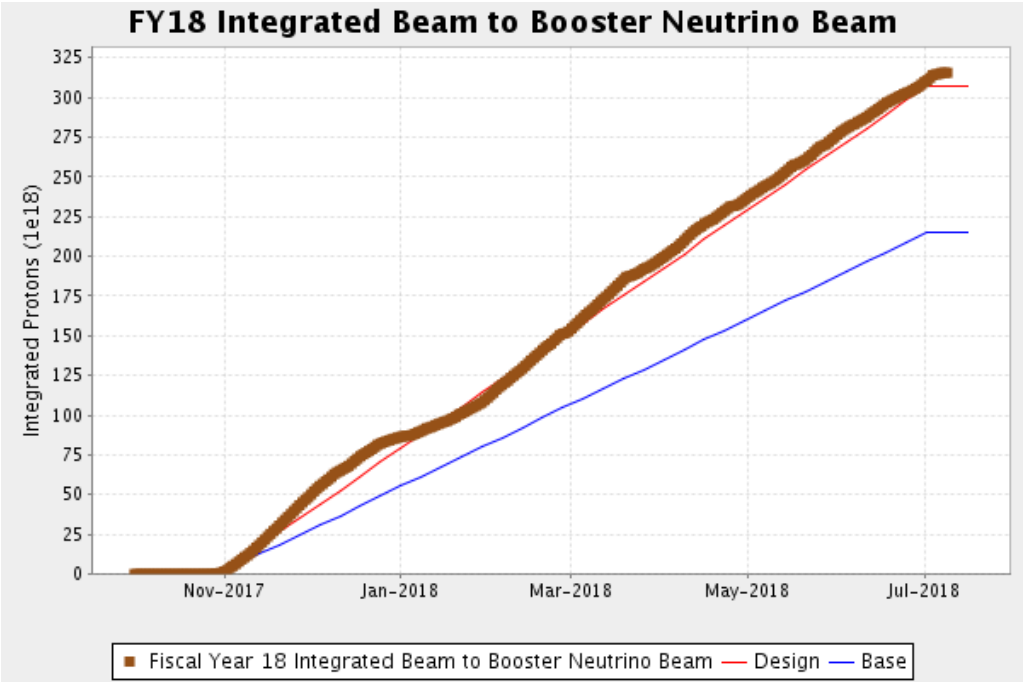
*New since last PAC*




Smooth and steady data taking

Efficient data acquisition

# Summary of Beam Delivery to MicroBooNE




(plot from Cons Gattuso)

Note: this past year, NoVA and g-2 were maxed out, Beam to BNB was "extra"….
Accelerators are running very well!

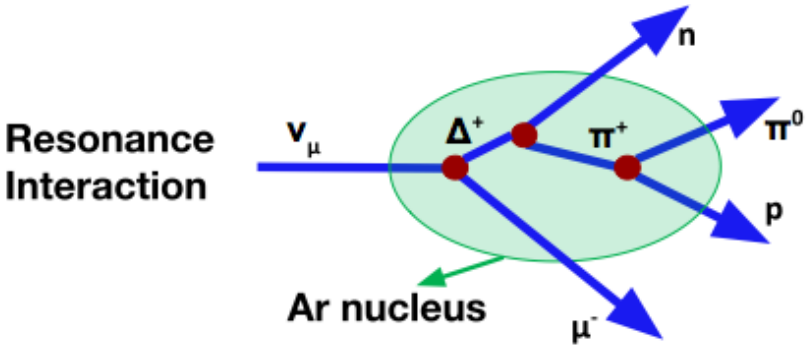
| MicroBooNE Run Period | POT collected |
|---|---|
| Run 1 (Oct 2015 – Oct 2016) | $3.6 \times 10^{20}$ |
| Run 2 (Oct 2016 – Mar 2017), new service boards | $2.0 \times 10^{20}$ |
| Run 3 (Mar 2017 – present), full CRT | $4.0 \times 10^{20}$ |
| total | $9.6 \times 10^{20}$ |

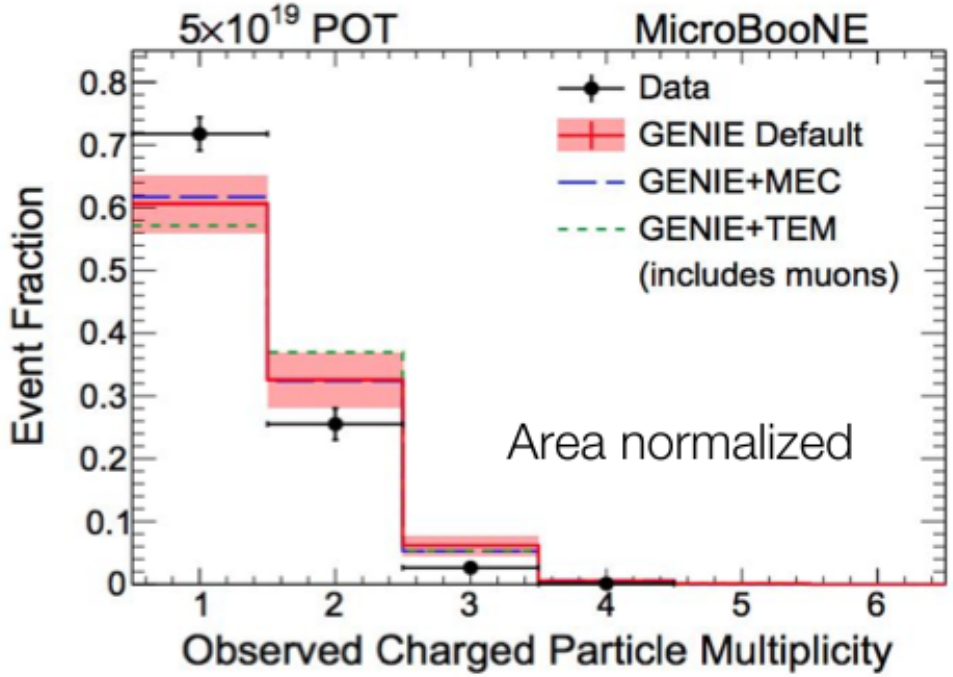
- $9.6 \times 10^{20}$ POT collected to date (73% of request)
- $4.0 \times 10^{20}$ POT with full CRT (42% of total)
- FY18: $3.1 \times 10^{20}$ POT
- Project that we will get to our $13.2 \times 10^{20}$ POT beam request by December 2019 (56% with CRT)

# Charged Particle Multiplicity

- Study the charged particle multiplicity (CPM) in $\nu_\mu$ interactions
- Powerful way to validate nuclear models (and generators)
- First detailed look on how well GENIE models Argon
- First physics result!

**Example of neutrino interaction with CPM = 2**



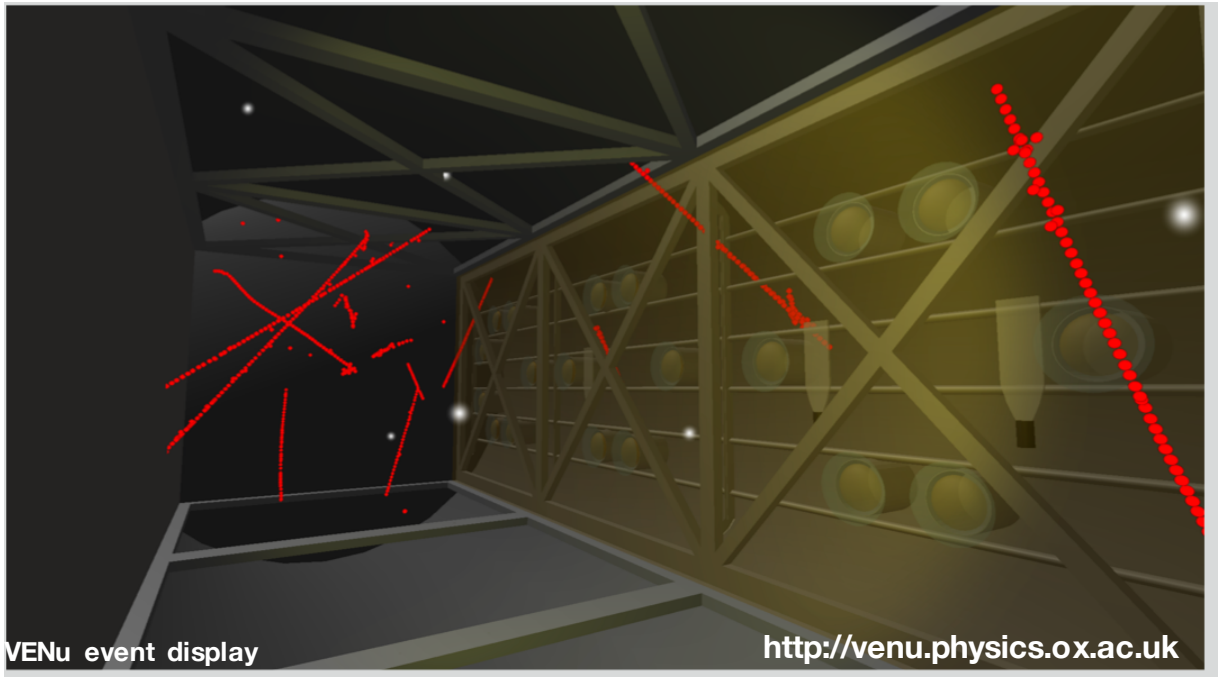




"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

# $\nu_\mu$ CC Inclusive measurement

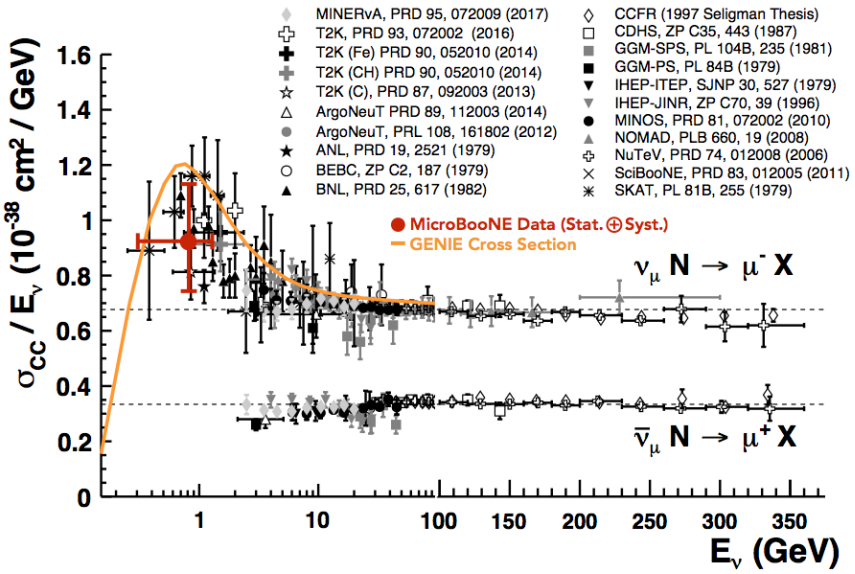
Inclusive $\nu_\mu$ CC interactions : first detailed look in Argon!

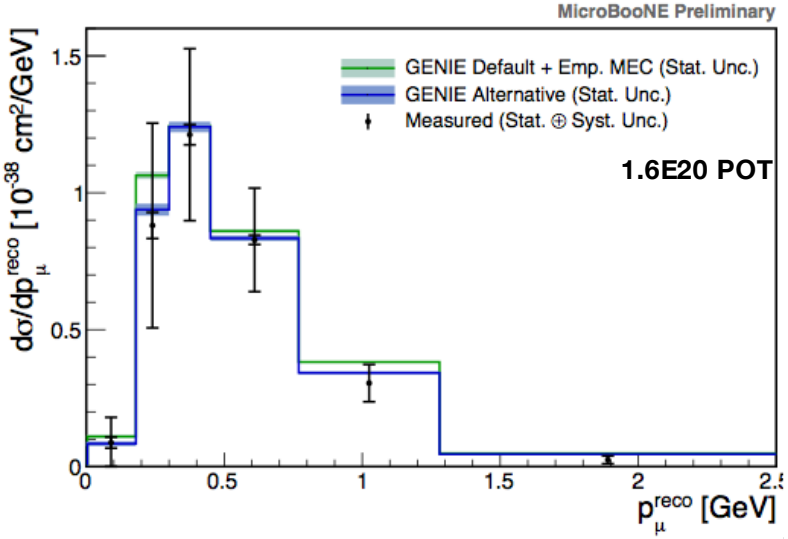
- Measured by many other experiments, making it a great benchmark
- Validates reconstruction techniques and analysis process for oscillation analysis
- Constrains backgrounds in oscillation analysis
- Directly relevant to DUNE $\nu_\mu$ CC signal

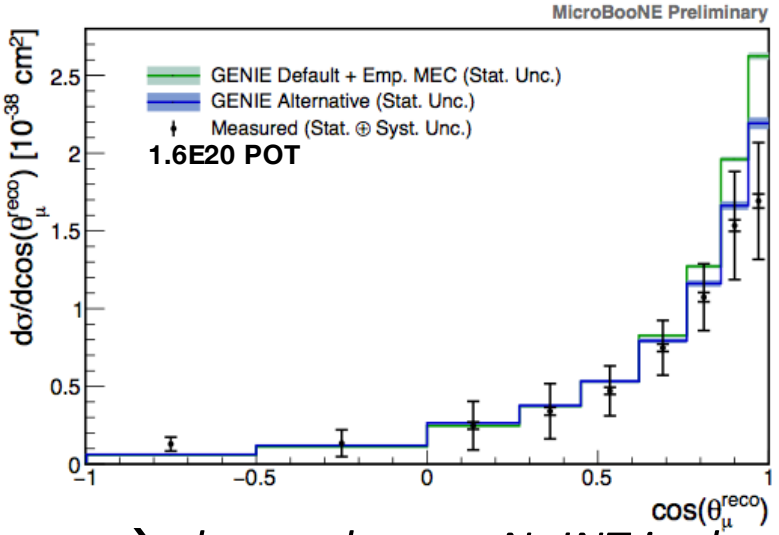


# $\nu_\mu$ CC Inclusive measurement

- Includes contained and exiting muons (takes advantage of MCS technique tuned for Argon)
- Includes flux, cross section, and first detector systematics
- Absolute cross section measurement



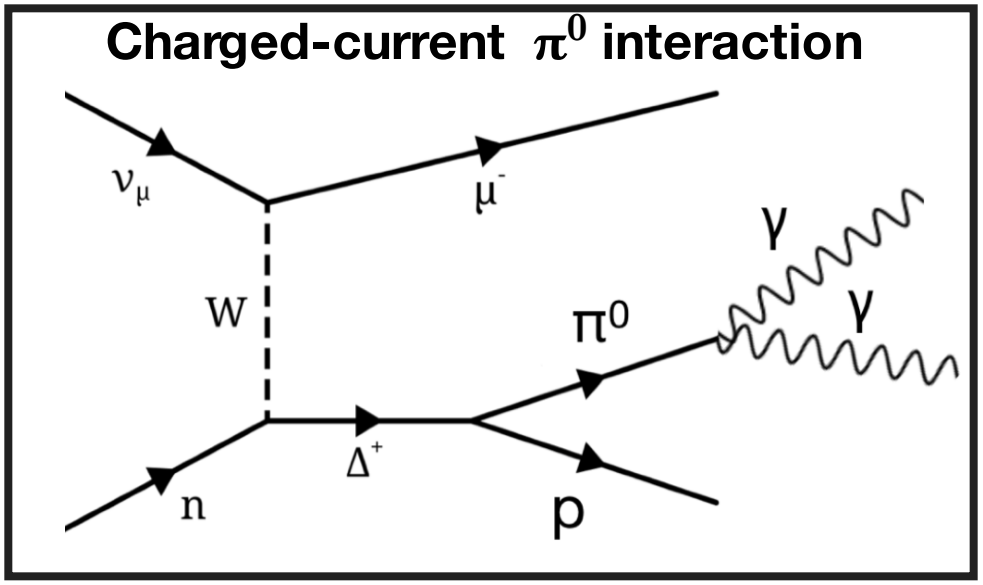



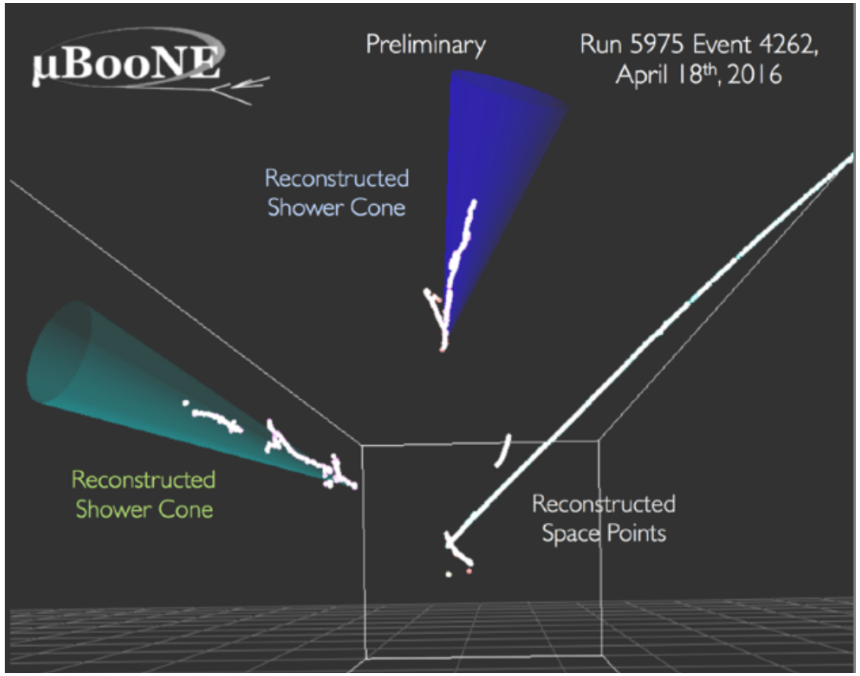

*Next steps: double differential xsec measurement → plan to show at NuINT in the fall*

Public Note: MICROBOONE-NOTE-1045-PUB, 2018

# CC-$\pi^0$ cross-section measurement

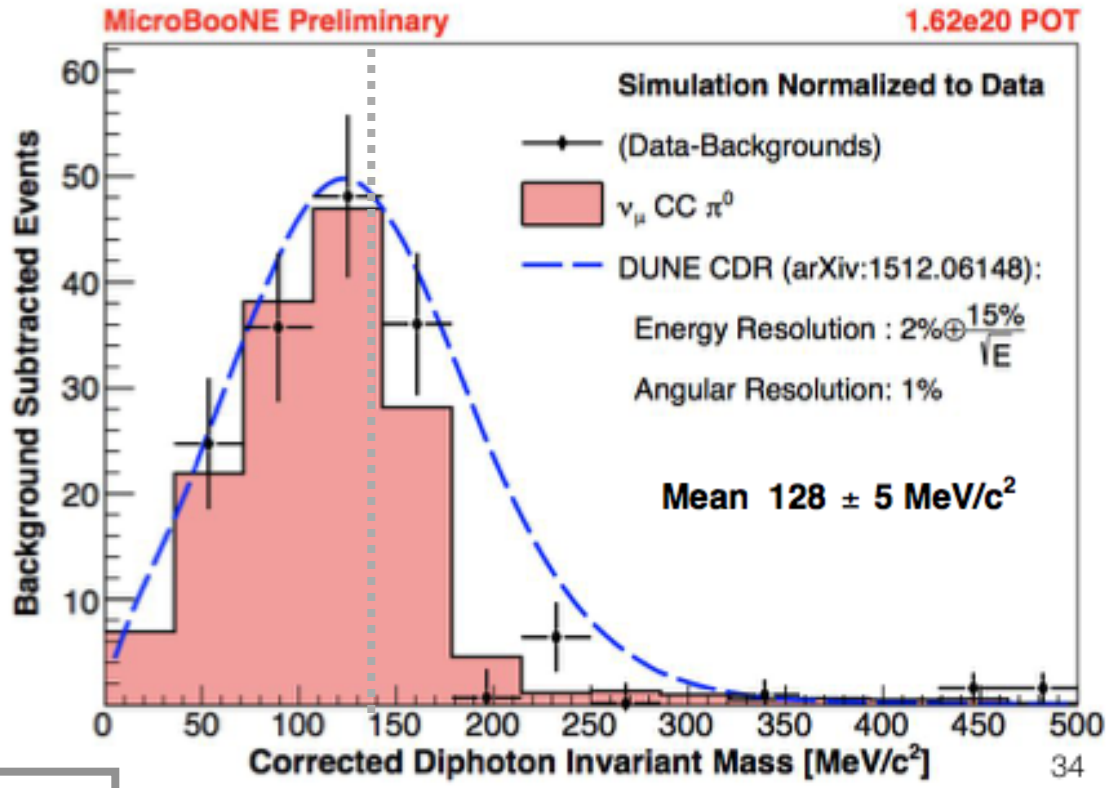
- First measurement on Argon, first look at events with showers!
- Understanding $\pi^0$ is a crucial step towards searching for low-energy excess:



# CC-$\pi^0$ reconstruction and selection

Reconstruction of the $\pi^0$ mass peak:




Total cross section:

Mass of $\pi^0$: 135 MeV

$$\left\langle \sigma^{\nu_\mu \mathbf{CC}\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16\ [\text{stat.}] \pm 0.60\ [\text{syst.}]) \times 10^{-38}\ \frac{\text{cm}^2}{\text{Ar}}$$

*Next steps: Improved analysis, more statistics → differential cross-section measurement*

Public Note: MICROBOONE-NOTE-1032-PUB, 2018

# Systematics

first quantified in summer 2018 cross section results

## Flux systematics

- **Hadron production** uncertainties
- **Other beam uncertainties**: horn current, skin depth, p, π cross sections
  - → *Propagated using multisims, according to public note: Booster Neutrino Flux Prediction at MicroBooNE, MICROBOONE-NOTE-1031-PUB (2018)*

## Cross section systematics

- Uncertainties on > 30 default parameters in GENIE
  - → *Propagated using GENIE's built-in multisim framework*

## Detector response systematics

- **Space charge effect** – varied simulation to better match measured effect
- **Induced charge** – simulated on longer spatial range than in standard MC
- **Light yield** – substituted improved model for standard MC model
- **Misconfigured and frequently saturating channels** – varied this effect in simulation
- **Wire response functions** – varied simulation to better match measured wire response
- **Longitudinal & transverse diffusion** – varied within range of world LAr data
- **Noise on TPC wires & PMTs** – varied within measured range
- **Light outside TPC** – varied light yield in cryostat but outside TPC
- **Electron lifetime** – reduced to lower range consistent with measurements
- **Recombination** – replaced MC model with alternative model
  - → *Propagated using unisims; more detail in public note for CC inclusive cross section: MICROBOONE-NOTE-1045-PUB (2018)*

**Also included:** Uncertainties on cosmic ray simulation, flash timing, and POT counting

# Pioneering different analysis techniques for this physics for SBN and DUNE

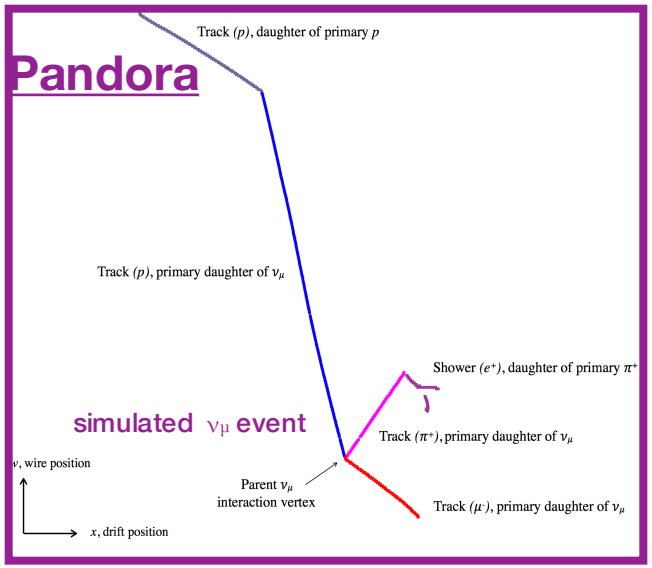
- In the early years of MicroBooNE many ideas on how to solve the automatic reconstruction problem
  - Entire phase space of possible solutions reviewed at some point!
- Currently, effort falls into three general categories
  - 2D pattern recognition, then match across planes to form 3D objects:
    - Pandora <— Currently the primary path for analyses
    - TrajCluster
  - "Pure" 3D approaches: <— Very promising but still lots of work to do
    - Combining 2D hits to form 3D space points to run pattern recognition
      - "SpacePointSolver", "Cluster3D" <— Both in LArSoft
    - WireCell: tomographic imaging using charge deposits on each plane
      - MicroBooNE public note due out this week
  - Brave new world: <— Even more promising but even more work to do
    - Deep Learning approaches continue to be pioneered by MicroBooNE. More information on early applications of this to MicroBooNE data can be found in "Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", JINST 12, p03011(2017), arXiv: 1611.05531

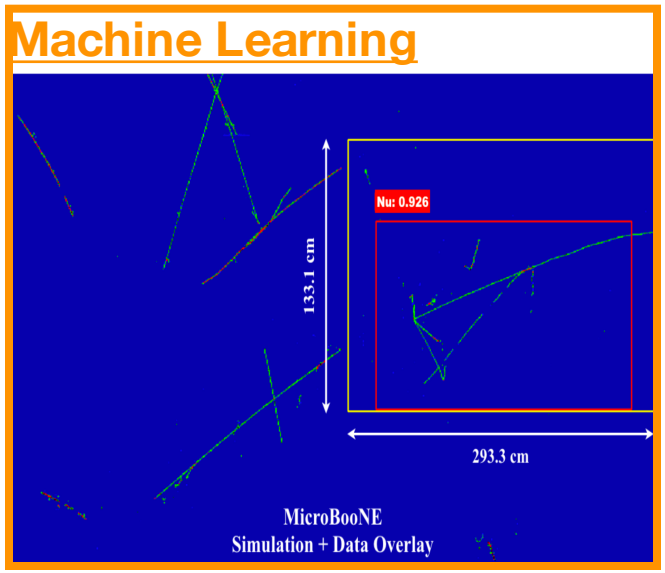
From Recent talk to LBNC: "SBN Coordinated Reconstruction/Analysis Strategy: With Lessons Learned from MicroBooNE" -Tracy Usher

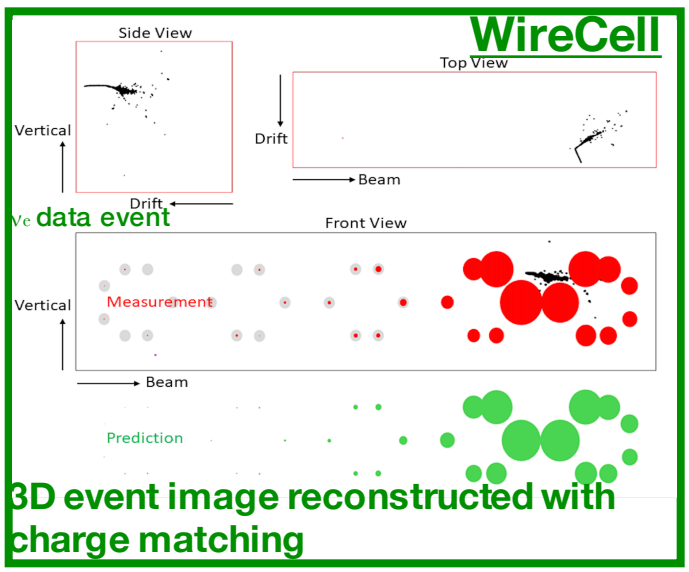
From LBNC closeout report: *"MicroBooNE, as the experiment currently with data, has made most progress on reconstruction and analysis tools – these are being made available to the other experiments in the LArSoft framework. "*

# Event reconstruction techniques

- Reached high level of sophistication
- Using these for cross section measurements (primarily Pandora) and for our signature analysis




*"The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", Eur. Phys. J. C78, 1, 82 (2018)"*

*"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", JINST 12, P03011 (2017)*

Public Notes:

- "Vertex finding and reconstruction for contained two-track events in the MicroBooNE detector", MICROBOONE-NOTE-1042-PUB, 2018
- "Towards automated neutrino selection at MicroBooNE using tomorgraphic event reconstruction", MICROBOONE-NOTE-1040-PUB, 2018
- "Hunting muon neutrinos in microboone with deep learning techniques," MICROBOONE-NOTE-1051-PUB, 2018
- "Reconstruction performance studies with MicroBooNE data", MICROBOONE-NOTE-1049-PUB, 2018

# MicroBooNE Low Energy Excess, electron-based, analysis approaches

| Approach | Channel | Philosophy | Pros | Cons |
|---|---|---|---|---|
| Pandora | $\nu_e \rightarrow e^- + Np, N>0$<br>$\nu_e \rightarrow e^- + X$ | "Traditional" reconstruction (Pandora toolkit)[1] | Higher statistics, spans larger energy range, more MiniBooNE-like signal | More complex topology |
| Deep Learning | $\nu_e \rightarrow e^- + 1p$ below 600 MeV | DL[2] + "traditional" reconstruction | Simple topology, Better $E_\nu$ determination, lower backgrounds | Low statistics, subset of what MiniBooNE looked at |
| Wire Cell | $\nu_e \rightarrow e^- + X$<br>X depends on sensitivity | Robust noise filtering, signal processing.[3] Image and reconstruct in 3D | 2 plane reconstruction, 3D imaging, more inclusive → highest stats | Most complex final states → greater demands on reconstruction (need calorimetry) |
| TrajCluster | Fully inclusive $\nu_e$ CC selection | "traditional" reconstruction | More inclusive → highest stats, less model-dependent, DUNE-like signal | Complex final states → greater demands on reconstruction (need calorimetry) |

[1]Eur.Phys.J. C78, 82 (2018)
[2]JINST 12 P03011, 2017
[3]JINST 12 P08003, 2017,

# MicroBooNE Low Energy Excess, electron-based, analysis approaches

| Approach | Channel | Philosophy | Pros | Cons |
|---|---|---|---|---|
| Pandora | $\nu_e \rightarrow e^- + Np, N>0$ | "Traditional" | Higher statistics, | More complex topology |
| Deep Learning | | | | Low statistics, subset of what MiniBooNE looked at |
| Wire Cell | | | | Most complex final states → greater demands on reconstruction (need calorimetry) |
| TrajCluster | | | dependent, DUNE-like signal | Complex final states → greater demands on reconstruction (need calorimetry) |

Best of each technique likely to be adopted by all:

- 2D deconvolution and signal processing
- Cosmic ray removal
- Proton ID
- …

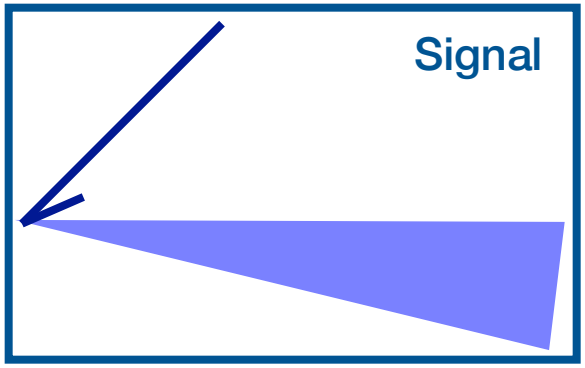
Systematic Errors supported and coordinated for all analyses by Systematics group (new since last PAC)

Pandora as example…

[1]Eur.Phys.J. C78, 82 (2018)
[2]JINST 12 P03011, 2017
[3]JINST 12 P08003, 2017,

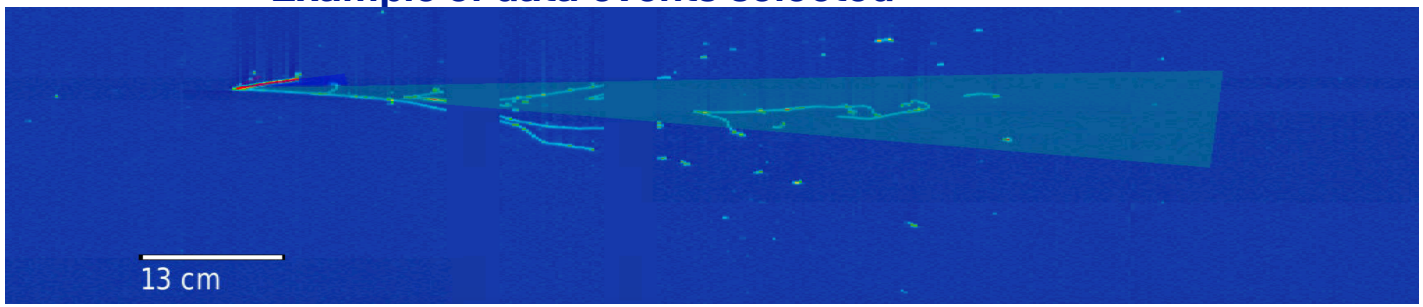
# $\nu_e$ analysis

Pandora team focuses on the signal most similar to the MiniBooNE CC0π definition: 1 electron + N protons

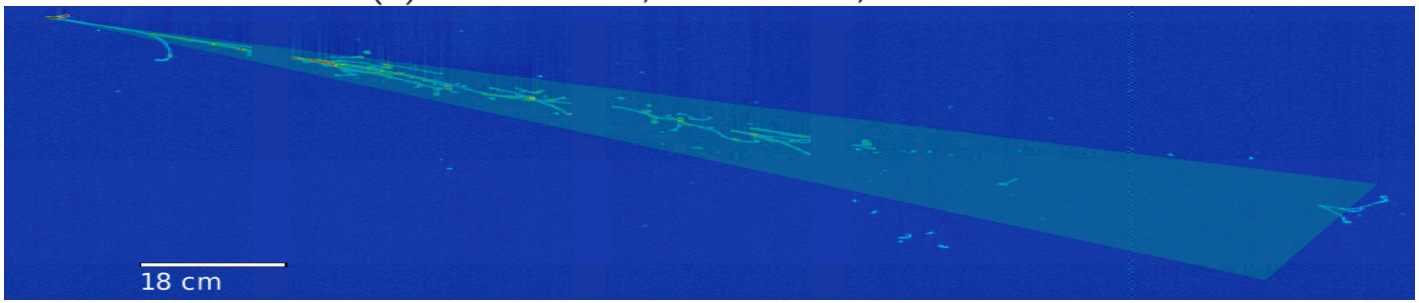



Shower selection for 3 different $\nu_e$ data candidate events in BNB in 5E19 sample

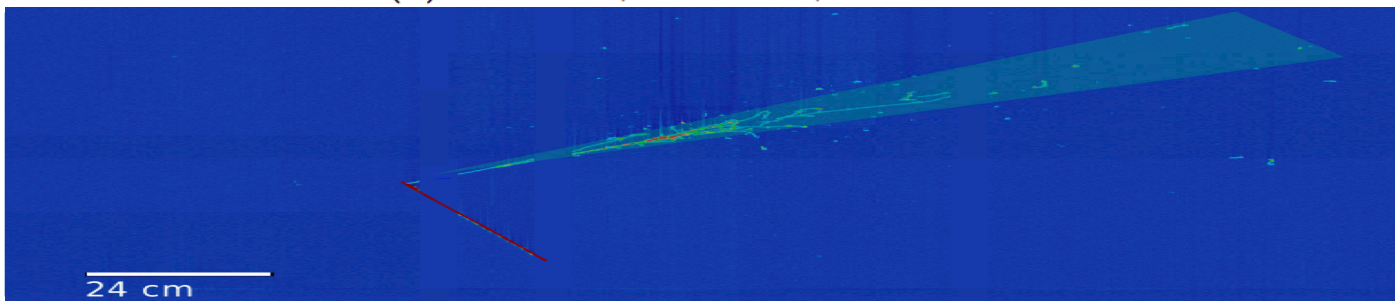
**Example of data events selected**




(a) Event 1515, Subrun 30, Run 5328




(b) Event 31, Subrun 0, Run 5513

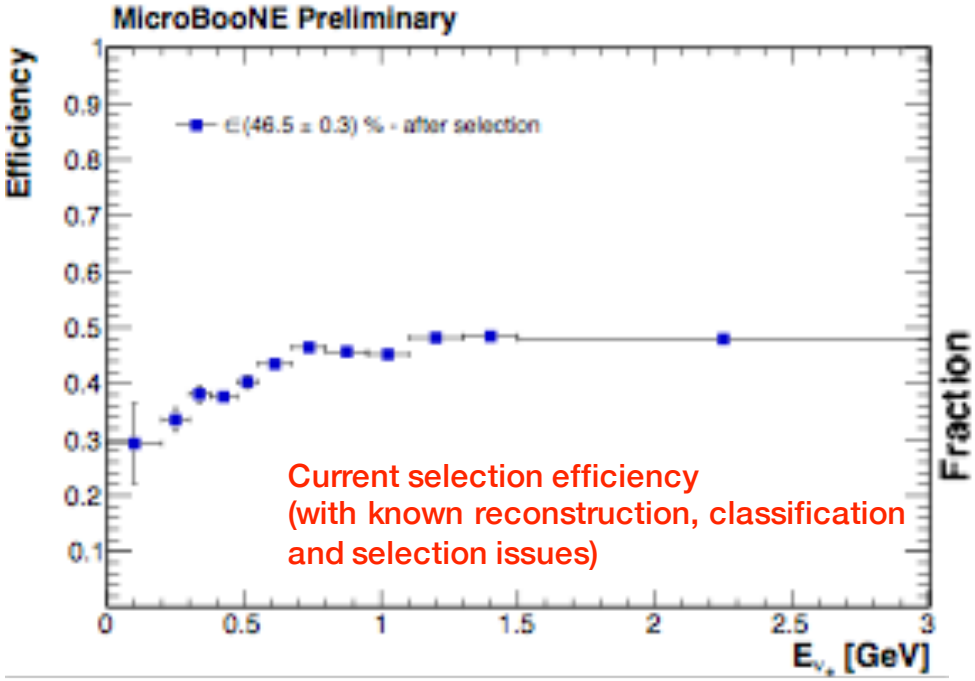


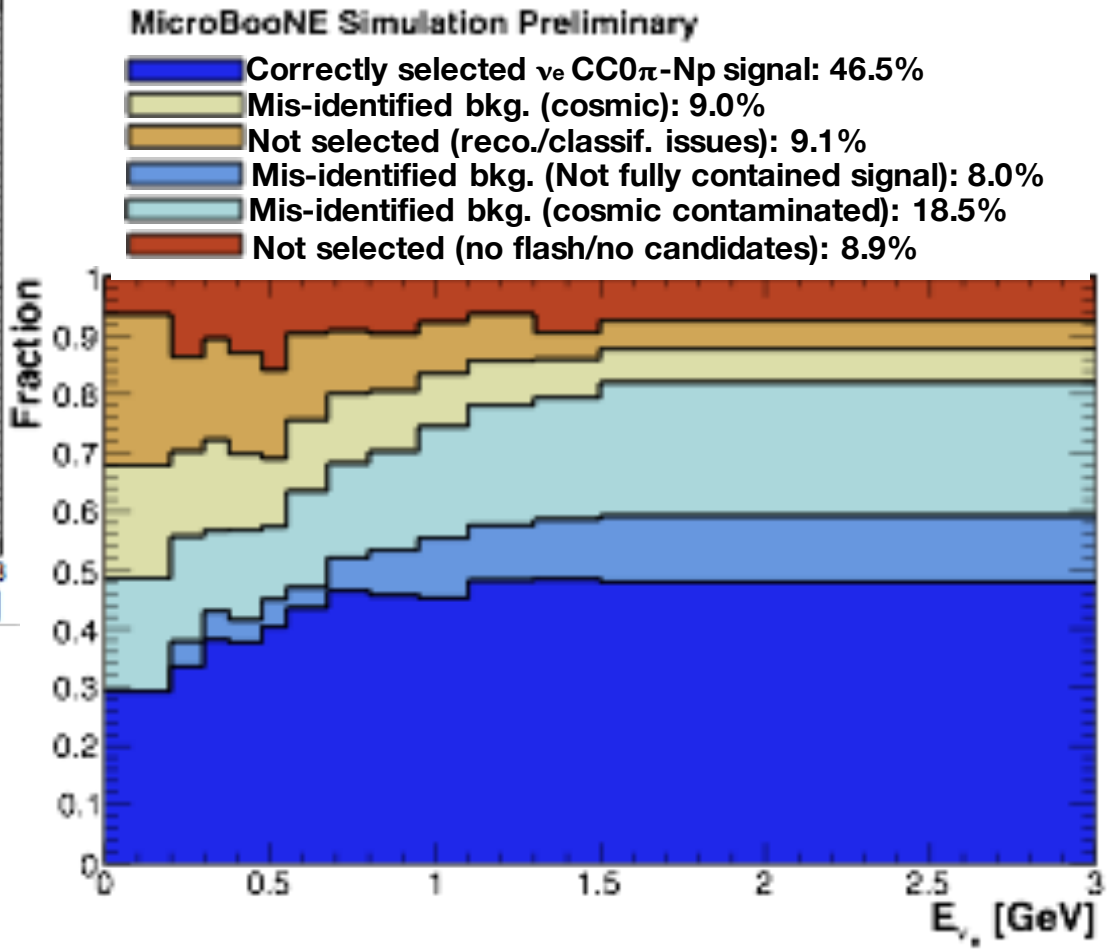

(c) Event 3710, Subrun 74, Run 5906

MICROBOONE-NOTE-1038-PUB, 2018

# $\nu_e$ analysis

## Selection efficiency for 1e+ Np



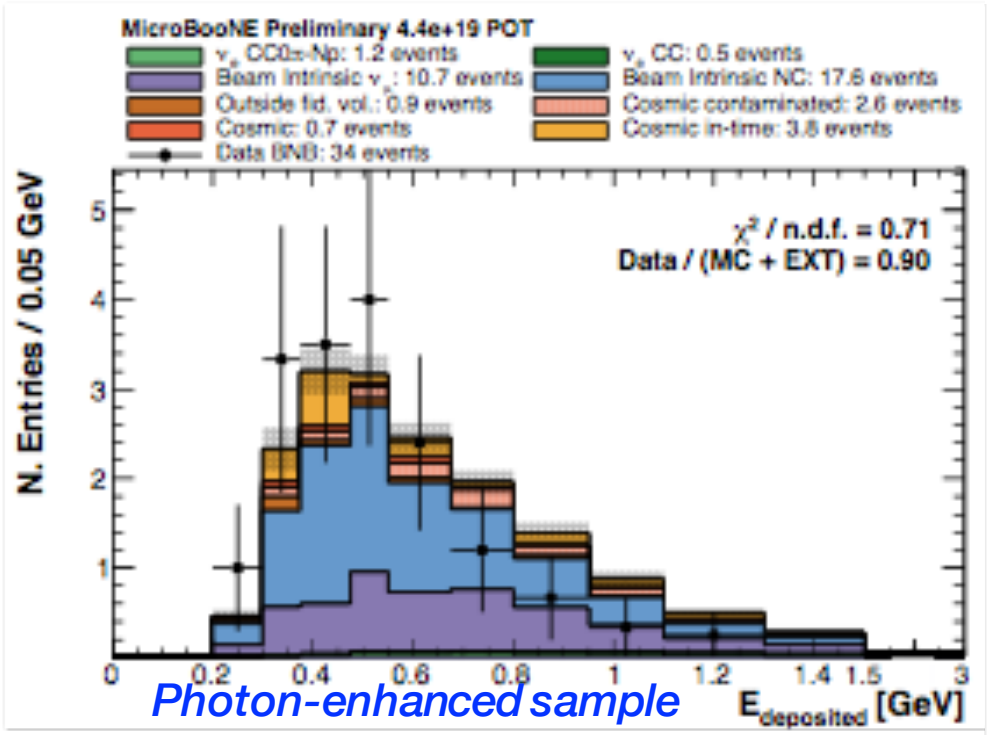

Next reconstruction and data/MC production informed by mis-IDs in this and other analyses….
(will come back to this…)

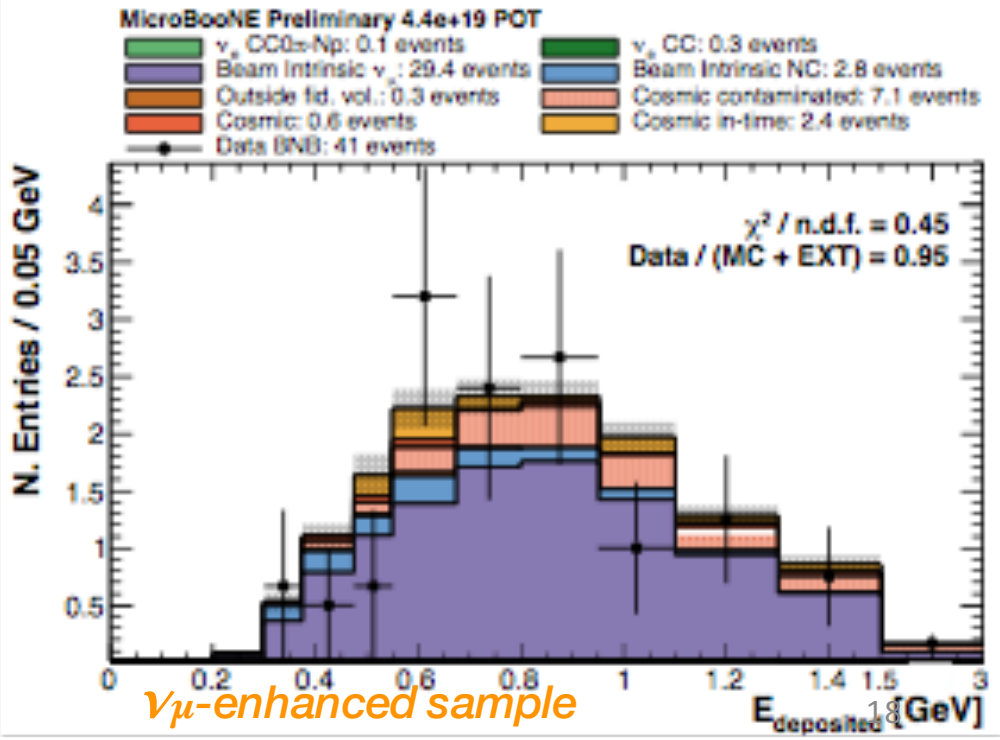
MICROBOONE-NOTE-1038-PUB, 2018

# Validating $\nu_e$ analysis

- Small unblinded data sample available for testing ($4.4 \times 10^{19}$ POT)
- Validation using side-bands ($\nu_\mu$ charged current or neutral current events)
- Use cuts to select non-$\nu_e$ events:
  - ✓ dE/dx of showers
  - ✓ Distance between shower start and track start
  - ✓ Proton identification score (from boosted decision tree)

MICROBOONE-NOTE-1038-PUB, 2018



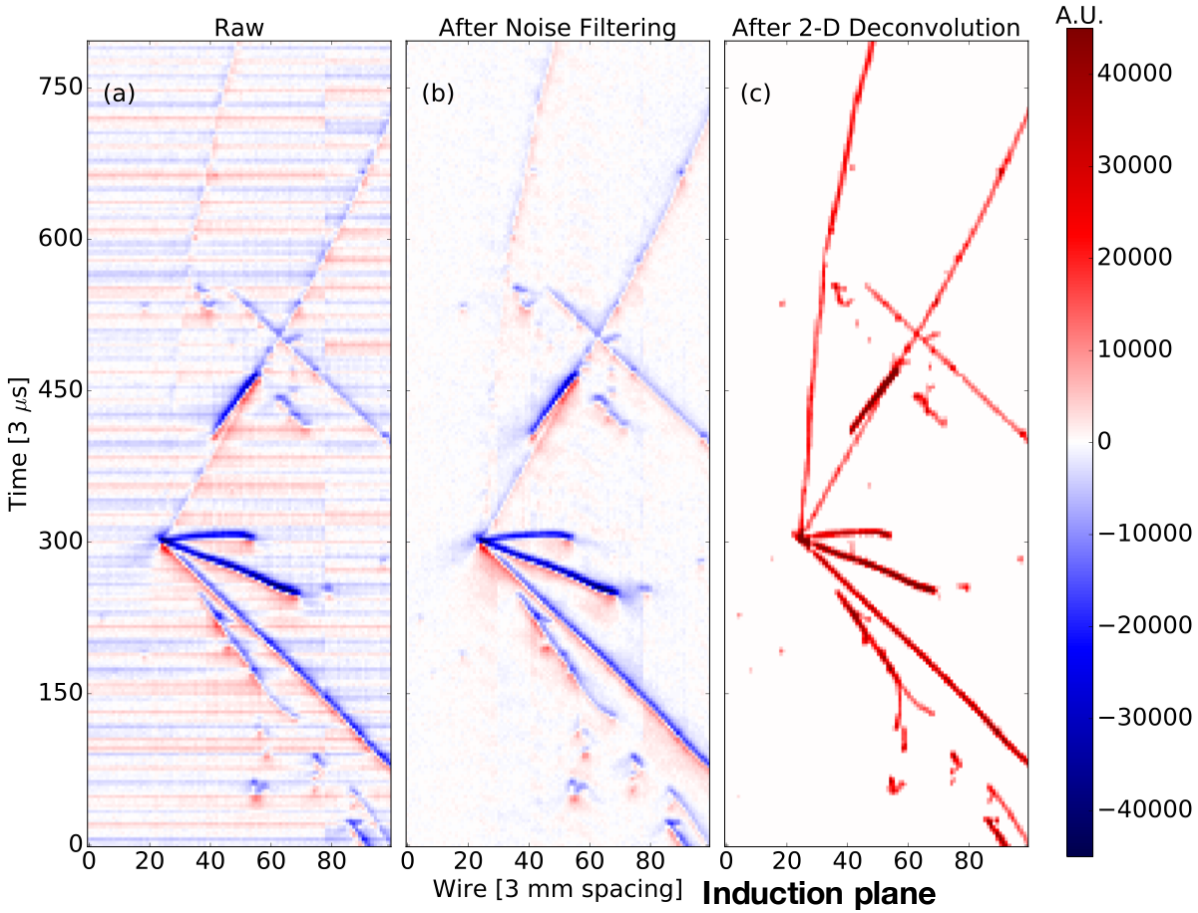



# Low-energy excess analysis


- The currently ongoing $\nu_e$ (and other) analyses have informed us of where improvements/iterations may be impactful…
  - Implementation of 2D deconvolution and Signal processing
  - Improved cosmic removal techniques + cosmic-ray tagger system
  - Calorimetry on the 3 planes, improve the dE/dx measurements
  - Low energy reconstruction/classification improvements
  - Evaluation of dirt backgrounds
- Perform end-to-end analysis with these iterations
- Validate analysis with side-bands
- Use NuMI $\nu_e$ events to validate the analysis with high statistics
- Perform the single photon analyses

MICROBOONE Public Notes: 1038, 1041, 1043

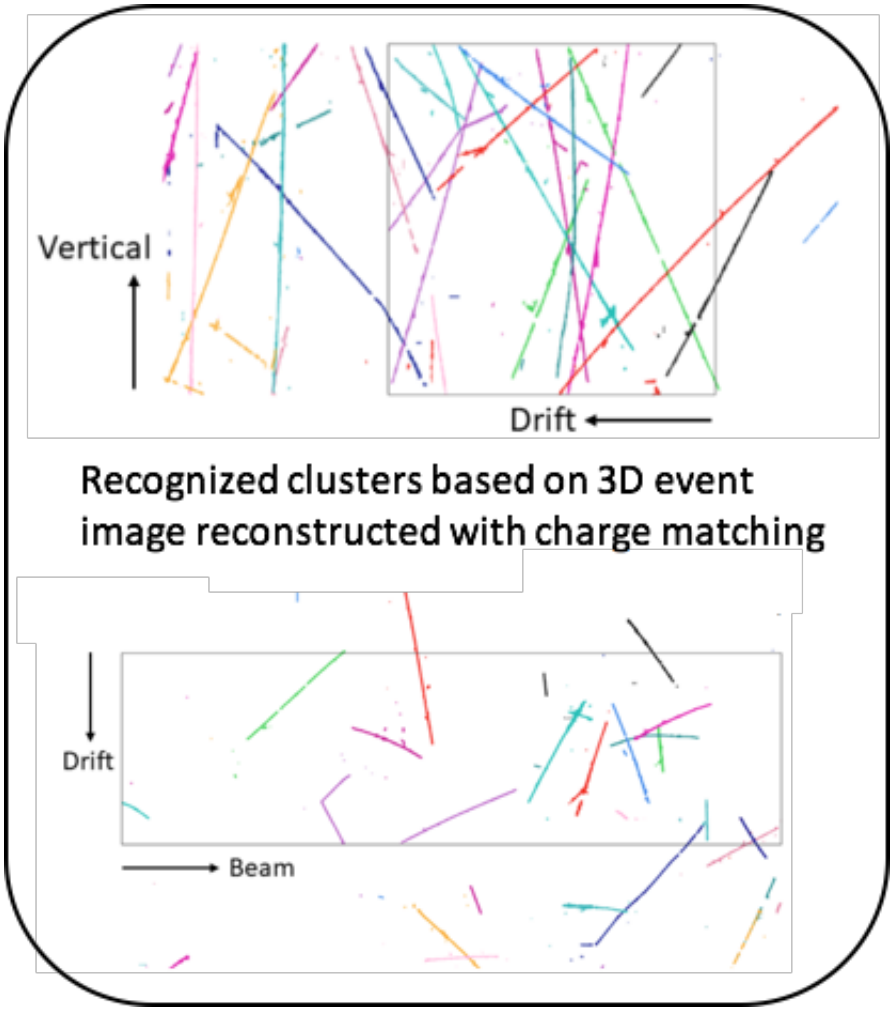
# Detailed characterization of the detector is key to our Physics and to our R&D mission for future detectors

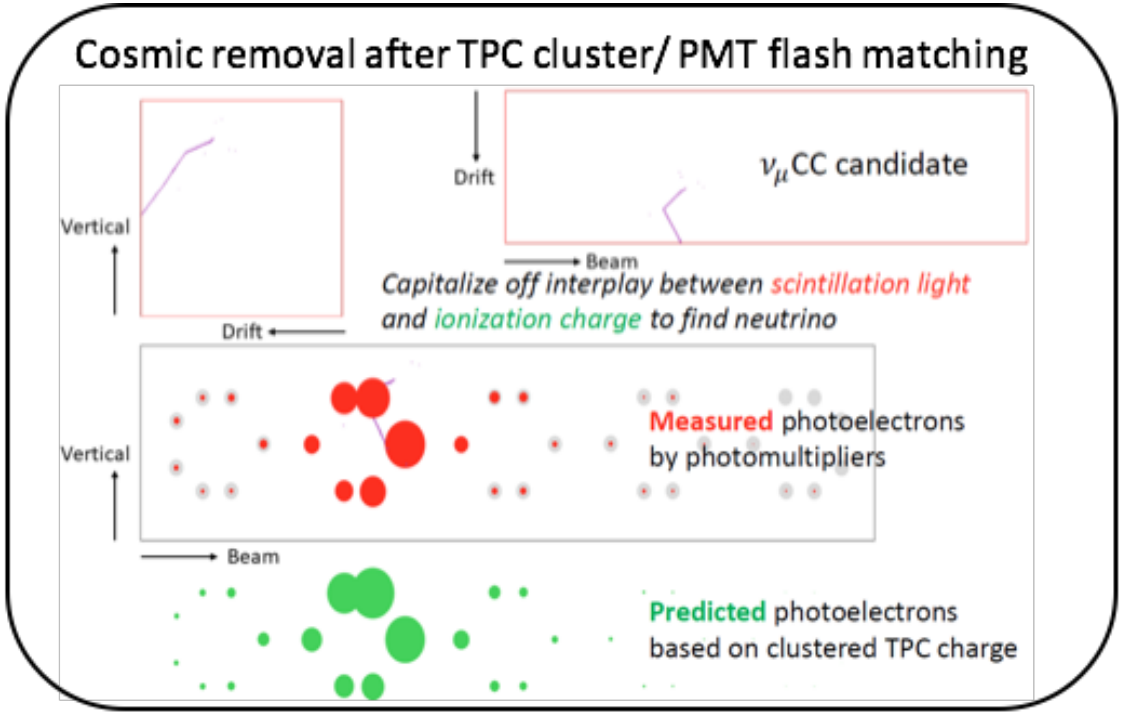



- Powerful filtering techniques can address many sources of noise
- Excellent characterization of multiple wire signal response (2d-deconvolution)
- Robust signal processing allows calorimetry in all three planes (**enabling induction planes**)
- Note: not been done before….

- *"Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE"*, arXiv:1804.02583, accepted by JINST
- *"Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation"*, arXiv:1802.08709, accepted by JINST
- *"Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC"*, arXiv:1705.07341, JINST 12, P08003 (2017)
- "Detector Calibration using through going and stopping muons in the MicroBooNE LArTPC", MICROBOONE-NOTE-1048-PUB, 2018

# Wirecell



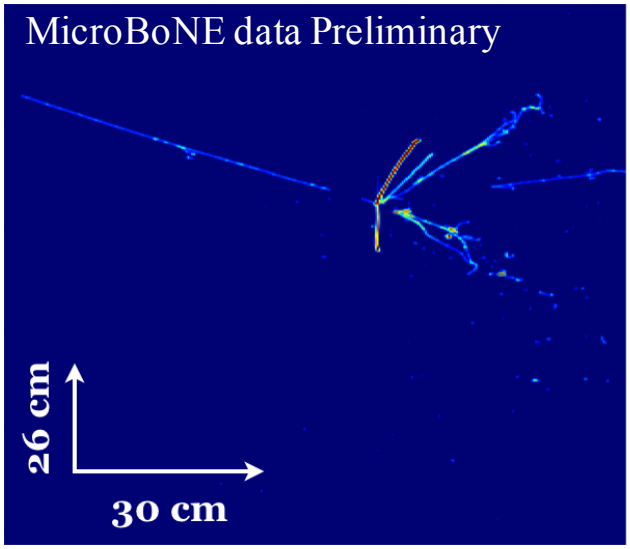

Publications and Public Notes

- “Three-dimesional imaging for large LArTPCs” JINST 13, P05032
- MICROBOONE-NOTE-1040-PUB

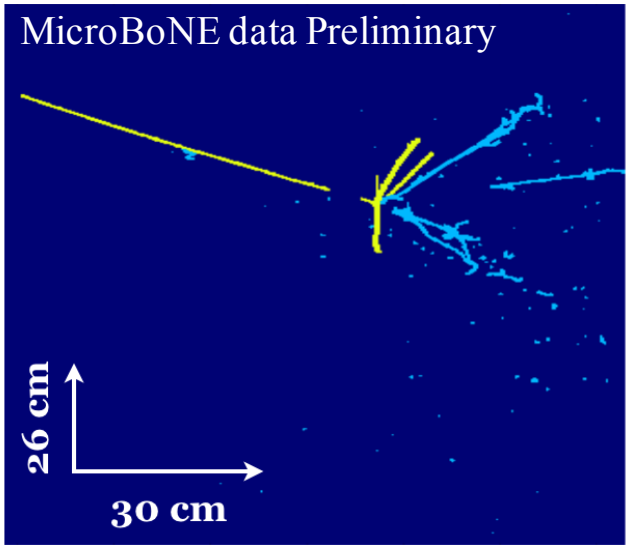
Xin Qian, DOE ECA: "Detector Development towards Precision Measurements of Neutrino Mixing", 2014.
Chao Zhang, DOE ECA: “"Optimization of Liquid Argon TPCs for Nucleon Decay and Neutrino Physics", 2017

# Deep Learning

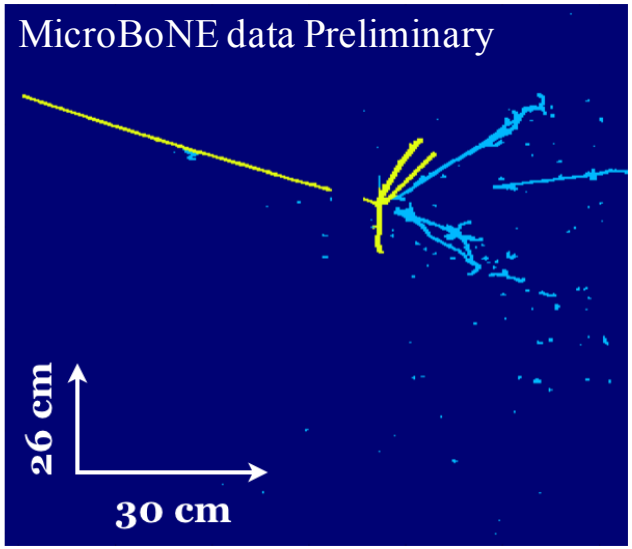
- Pioneering work on a novel reconstruction technique!
- Early application to MicroBooNE data published: *"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber"* (JINST 12 p03011 (2017)
- Recent work in labeling pixel's as tracks or showers, In preparation for submission: *"A Deep Neural Network for Pixel-Level Track/Shower Separation in a Liquid Argon Time Projection Chamber"*




Raw data




Physicist labeled

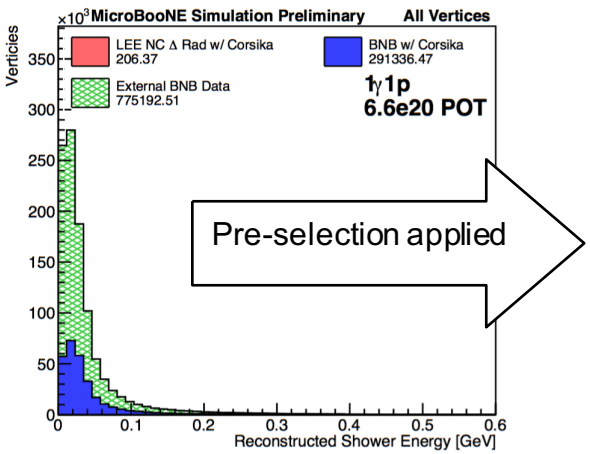



Network labeled

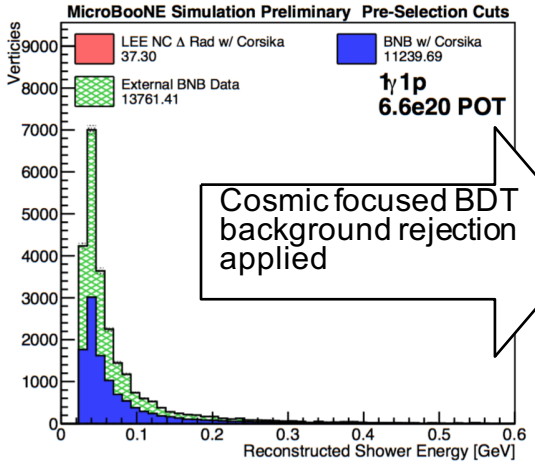
DOE ECA award to Kazu Terao, 2018: *"GPU/FPGA Accelerated Deep Learning Technique Development for Discovering Physics in Liquid Argon Time Projection Chambers."*

# LEE Single Photon Analysis

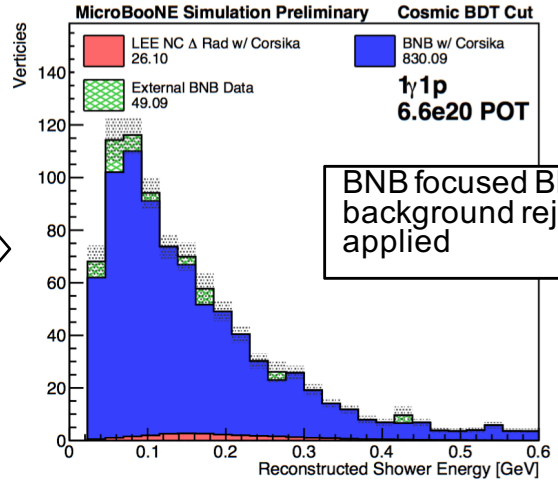
Starting with Pandora-reconstructed and vertex-optimized 1γ1p events...



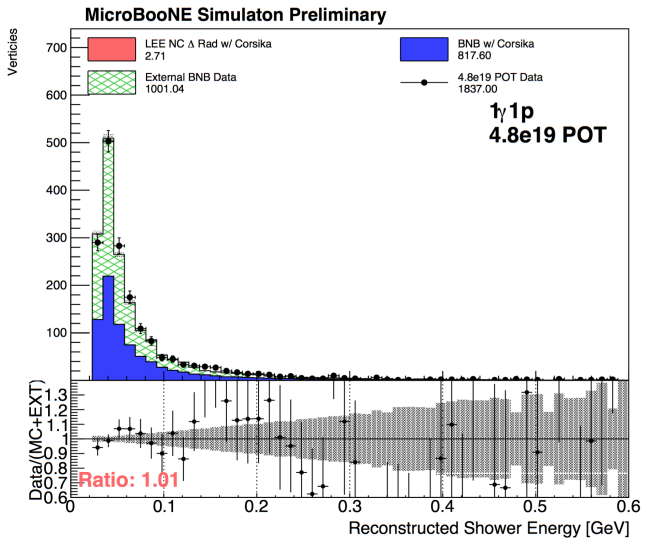

Pre-selection applied




Cosmic focused BDT background rejection applied

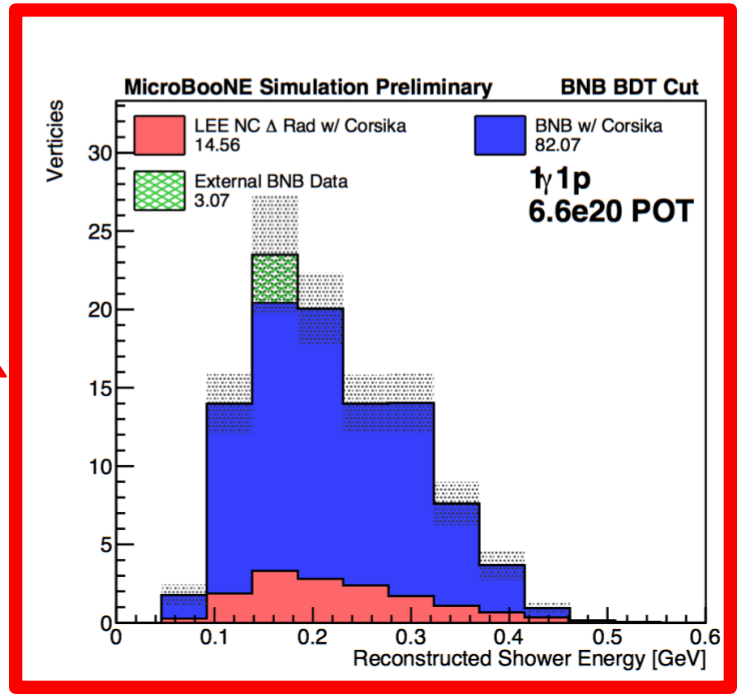



BNB focused BDT background rejection applied

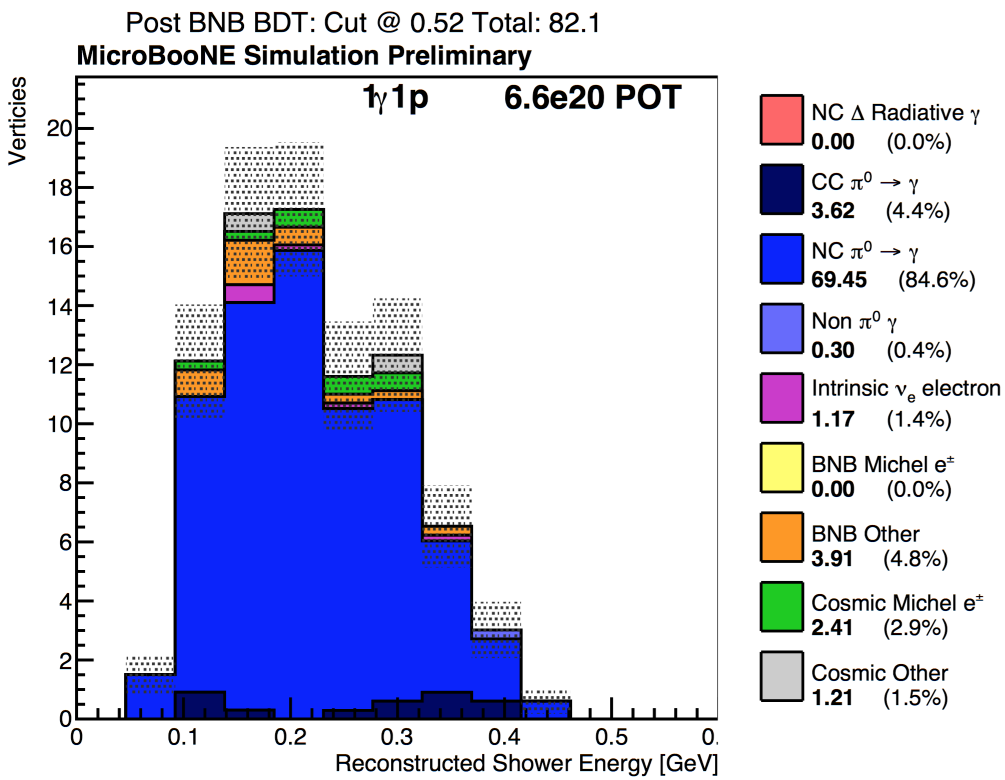



**Current state of analysis: validation on 4.8e19 POT unblinded data.**

**Final 1γ1p selection**

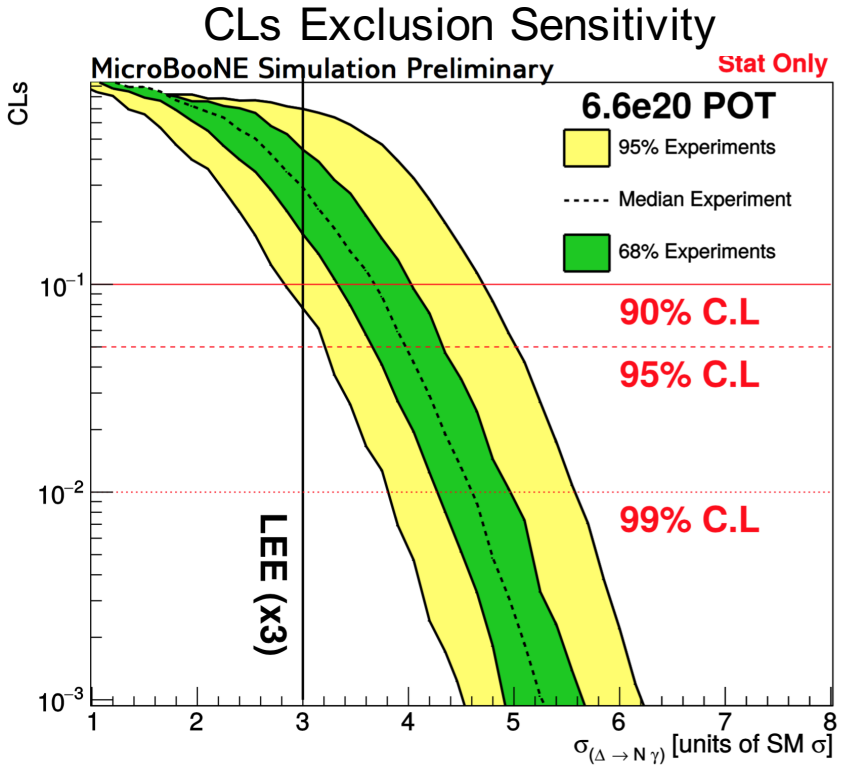


# LEE Single Photon Analysis




**Vast majority of remaining background comprised of NC $\pi^0 \rightarrow 2\gamma$ decay. Working on further background reduction strategies for NC $\pi^0 \rightarrow 2\gamma$ decay**

**Projected stats-only sensitivity on the 6.6e20 POT dataset would exclude a 4.6xSM cross-section at 99 % C.L. (photon LEE at 3xSM).**



July 2018

# MicroBooNE Collaboration


*University of Bern, Switzerland:* M. Auger, Y. Chen, A. Ereditato, D. Goeldi, I. Kreslo, D. Lorca, M. Lüethi, T. Mettler, J. Sinclair, M. Weber

*Brookhaven:* M. Bass, M. Bishai, H. Chen, W. Gu, X. Ji, J. Joshi, B. Kirby, Y. Li, X. Qian, B. Viren, H. Wei, B. Yu, C. Zhang

*University of Cambridge*: J. Anthony, L. Escudero Sanchez, J. Jan de Vries, J. Marshall, A. Smith, M. Thomson

*University of Chicago*: A. Mastbaum, D.W. Schmitz

*University of Cincinnati*: R. Grosso, R.A. Johnson

*Colorado State University:* I. Caro Terrazas, R. LaZur, M. Mooney, H. Rogers

*Columbia University*: D. Cianci, J. Crespo, V. Genty, Y.-J. Jwa, G. Karagiorgi, M. Ross-Lonergan, W. Seligman, M. Shaevitz, K. Sutton

*Davidson College*: B. Eberly

*Fermilab*: B. Baller, D. Caratelli, R. Castillo Fernandez, F. Cavanna, G. Cerati, K. Duffy, H. Greenlee, C. James, W. Ketchum, M. Kirby, T. Kobilarcik, S. Lockwitz, A. Marchionni, S. Marcocci, C. Moore, O. Palamara, Z. Pavlovic, J.L. Raaf, A. Schukraft, E. Snider, P. Spentzouris, M. Stancari, J. St. John, T. Strauss, M. Toups, S. Wolbers, W. Wu, T. Yang, G.P. Zeller*, J, Zennamo

*Harvard University*: C. Adams, R. Guenette, J. Martin-Albo

*Illinois Institute of Technology*: R. An, I. Lepetic, B. Littlejohn, D. Martinez

*Kansas State University:* M. Alrashed, T. Bolton, G. Horton-Smith, V. Meddage, A. Rafique

*Lancaster University*: A. Blake, D. Devitt, A. Lister, J. Nowak

*Los Alamos:* G. Garvey, E-C. Huang, W.C. Louis, T. Thornton, R. Van de Water

*Manchester*: J. Evans, A. Furmanski, D. Gamez, O. Goodwin, P. Guzowski, C. Hill, K. Mistry, R. Murrells, D. Porzio, S. Söldner-Rembold, A.M. Szelc

*MIT:* A. Ashkenazi, R. Carr, J.M. Conrad, G. Collin, A. Diaz, O. Hen, A. Hourlier, J. Moon, A. Papadopoulou, L. Yates

*University of Michigan, Ann Arbor*: C. Barnes, R. Fitzpatrick, J. Mousseau, J. Spitz

*New Mexico State University*: V. Papavassiliou, S.F. Pate, L. Ren, S. Sword-Fehlberg, K. Woodruff

*Otterbein University*: N. Tagg

*University of Oxford*: G. Barr, M. Del Tutto, R. Soleti, W. Van De Pontseele

*University of Pittsburgh*: S. Dytman, L. Jiang, D. Naples, V. Paolone, A. Wickremasinghe

*Pacific Northwest National Laboratory:* E. Church, K. Bhattacharya, K. Wierman

*Saint Mary's University of Minnesota*: P. Nienaber

*SLAC*: M. Convery, L. Domine, L. Rochester, K. Terao, Y-T. Tsai, T. Usher

*Syracuse University*: A. Bhat, J. Esquivel, P. Hamilton, G. Pulliam, M. Soderberg

*Tel Aviv University*: E. Cohen, E. Piasetzky

*University of Tennessee, Knoxville*: S. Gollapinni, A. Mogan, W. Tang, G. Yarbrough

*University of Texas at Arlington*: J. Asaadi, Z. Williams

*Tubitak Space Technologies Research Institute, Turkey*: F. Bay

*Tufts University:* K. Mason, J. Mills, R. Sharankova, T. Wongjirad

*Virginia Tech:* L. Gu, C. Mariani, M. Murphy, V. Pandey

*Yale*: S. Balasubramanian, L. Cooper-Troendle, B.T. Fleming*, D. Franco, E. Gramellini, A. Hackenburg, X. Luo, B. Russell, G. Scanavini, S. Tufanli


180 collaborators
32 institutions (7 non-U.S.)
44 postdocs (18% international)
56 grad students (32% international)

55% students and postdocs
24% women
21% international collaborators

*spokespeople

| Name | Position taken after MicroBooNE postdoc |
|---|---|
| Roberto Acciarri | Applications Physicist, Fermilab |
| Jonathan Asaadi | Assistant Professor, Univ of Texas, Arlington |
| Andy Blake | Lecturer, Lancaster University |
| Ben Carls | Data Scientist, ComEd |
| Eric Church | Scientist, PNNL |
| Michael Cooke | AAAS Science & Technology Fellow, DOE |
| Brandon Eberly | Assistant Professor, Davidson College |
| Sowjanya Gollapinni | Assistant Professor, Univ of Tennessee, Knoxville |
| Nick Graf | Data Scientist, Allstate |
| Roxanne Guenette | Assistant Professor, Harvard |
| Leonidas Kalousis | Research Associate, Vrije Universiteit Brussel |
| Teppei Katori | Lecturer, Queen Mary University London |
| Georgia Karagiorgi | Assistant Professor, Columbia University |
| Wes Ketchum | Associate Scientist, Fermilab |
| Bryce Littlejohn | Assistant Professor, IIT |
| John Marshall | Lecturer, University of Warwick (Sept 1) |
| David McKee | Assistant Professsor, Missouri Southern State |
| Tia Miceli | Data Scientist, Allstate |
| Mike Mooney | Assistant Professor, Colorado State University |
| Zarko Pavlovic | Applications Physicist, Fermilab |
| Anne Schukraft | Associate Scientist, Fermilab |
| Josh Spitz | Assistant Professor, Univ of Michigan, Ann Arbor |
| Jason St. John | Applications Physicist, Fermilab |
| Thomas Strauss | Associate Scientist, Fermilab |
| Andrzej Szelc | Lecturer, University of Manchester and Royal Society University Research Fellow |
| Kazu Terao | Associate Staff Scientist, SLAC |
| Matt Toups | Associate Scientist, Fermilab |
| Yun-Tse Tsai | Associate Staff Scientist, SLAC |
| Taritree Wongjirad | Assistant Professor, Tufts University |
| Tingjun Yang | Associate Scientist, Fermilab |

# MicroBooNE Postdoc Placement

Out of the 30 former MicroBooNE postdocs:

- 90% have stayed in particle physics
- 77% remain on MicroBooNE

Where did they end up?

- 50% University Faculty (15)
- 37% National Lab Physicist (11)
- 10% Private Sector (3)
- 3% Government (1)

# Impact on DUNE

(young people only!)

| | Job title, Institution | Current Role on DUNE |
|---|---|---|
| Matt Bass | Postdoc, BNL | Long-Baseline Physics Working Group Co-Convener |
| Sowjanya Gollapinni | Assist. Professor, UTK | Slow Controls & Cryo Instrumentation Consortium Leader<br>Calibration Task Force Co-Leader |
| Roxanne Guenette | Assist. Professor, Harvard | FD APA Installation and Integration Co-Convener |
| Georgia Karagiorgi | Assist. Professor, Columbia | DAQ Consortium Technical Leader |
| Zarko Pavlovic | App. Physicist, FNAL | Accelerator/Beam Interface Coordination Co-Convener |
| Xin Qian | Physicist, BNL | FD Reconstruction Co-Convener |
| Jen Raaf | Scientist, FNAL | Nucleon Decay Working Group Co-Convener |
| Mitch Soderberg | Assoc. Professor, Syracuse | FD APA Working Group Co-Convener |
| Andrzej Szelc | Lecturer, Manchester | FD APA Working Group Co-Convener |
| Matt Toups | Assoc. Scientist, FNAL | FD Photon Detector Working Group Co-Convener |
| Tingjun Yang | Assoc. Scientist, FNAL | FD Reconstruction Working Group Co-Convener<br>35-Ton Prototype Working Group Co-Convener |

21 of the 25 PDs who stayed in particle physics have ”cell divided” and brought new groups to MicroBooNE and DUNE

Many hold leadership positions already on DUNE

# Summary: what have we achieved?

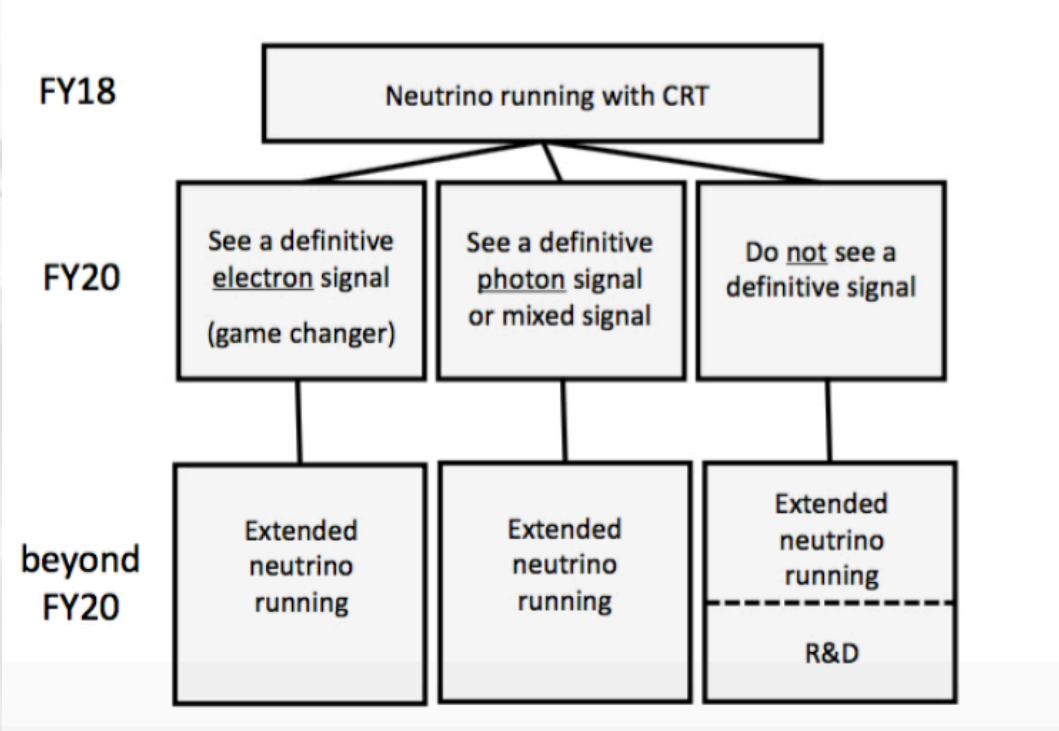
- Current results:
  - First absolute cross section measurements including differential measurements with
    - track and shower channels at the same time
    - including exiting tracks through usage of MCS
    - full angular coverage (1st time on argon!)
    - Verification of our reconstruction performance and resolution on data
    - First complete implementation and propagation of flux, cross section, and detector uncertainties through analysis chains
- In preparation of future results:
  - setup of electron and single photon analysis chains for different signal topologies and different reconstruction methods by parallel analysis teams
  - New data and MC production….

# Summary cont: Data and MC production…

- **Cross section analyses underway are proceeding** with Current data and MC production
- In parallel, **developing next generation data and MC** to address key issues to improve analyses and sensitivities:
  - Improvements to the base reconstruction:
    - Hit Finding, Track, Shower, Flash Reconstruction
  - Improvements in downstream reconstruction
    - Cosmic Ray tagging, vertex reconstruction, Calorimetry, particle ID
  - Improved calibrations
  - Improvements to Simulation
    - Physics– new/updated GENIE
    - Cosmic ray overlays
  - "LArG4 refactoring" – Induction plane charge and improved systematics
- **Integration of the CRT**: strategic focus has been to use Run1 data to set a path forward for next generation data and MC → now we will focus on integrating the CRT into this

# Summary

- Made enormous progress on understanding the MicroBooNE detector and the detector technology overall
- Multiple approaches in place for signature oscillation analysis
- Publishing first physics papers
- Cosmic backgrounds being addressed with new CRT system
- FY2020 represents a critical milestone
  - Collection of 13.2 x $10^{20}$ POT
  - SBND and ICARUS in operation
  - Final oscillations analysis to guide next steps wrt data taking
- Young people continue to do well!




***Great team → full speed ahead to FY2020***

# Physics results

NOW

## Publications

1. "Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

## Public Notes

1. " Electron-neutrino selection and reconstruction in the MicroBooNE LArTPC using the Pandora multi-algorithm pattern recognition", MICROBOONE-NOTE-1038-PUB, 2018
2. "The MicroBooNE Search for Single Photon Events", MICROBOONE-NOTE-1041-PUB, 2018
3. "MicroBooNE low-energy excess signal prediction from unfolding MiniBooNE Monte-Carlo and data", MICROBOONE-NOTE-1043-PUB, 2018
4. "Booster Neutrino Flux Prediction at MicroBooNE", MICROBOONE-NOTE-1031-PUB, 2018
5. "First measurement of muon neutrino charged-current neutral pion production in LArTPC", MICROBOONE-NOTE-1032-PUB, 2018
6. "First measurement of muon neutrino charged-current inclusive cross-section measurement in MicroBooNE", MICROBOONE-NOTE-1045-PUB, 2018
7. "*Towards measurements of nuclear effects in MicroBooNE",* MICROBOONE-NOTE-1046-PUB, 2018
8. "Electron-neutrino reconstruction in MicrobooNE using the Pandora pattern reconstruction", MICROBOONE-NOTE-1038-PUB, 2018
9. "Search for NC single photon events in MicroBooNE", MICROBOONE-NOTE-1041-PUB, 2018
10. "MicroBooNE tests of the MiniBooNE low-energy excess", MICROBOONE-NOTE-1043-PUB, 2018
11. "Booster Neutrino Flux Prediction at MicroBooNE", MICROBOONE-NOTE-1031-PUB, 2018

# Reconstruction and Calibration results NOW

## Publications

1. *"The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", arXiv:1708.03135, Eur. Phys. J. C78, 82 (2018)*
2. "Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter", arXiv:1707.09903, JINST 12, P12030 (2017)
3. "Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC", arXiv:1704.02927, JINST 12, P09014 (2017)
4. "Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering", arXiv:1703.06187, JINST 12 P10010 (2017)
5. *"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon TPC", arXiv:1611.05531, JINST 12, P03011 (2017)*

## Public Notes

1. "Reconstruction Performance Studies with MicroBooNE Data in Support of Summer 2018 Analyses", MICROBOONE-NOTE-1049-PUB, 2018
2. "Tomographic Event Reconstruction with MicroBooNE Data", MICROBOONE-NOTE-1040-PUB, 2018
3. "Vertex finding and reconstruction for contained two-track events in the MicroBooNE detector", MICROBOONE-NOTE-1042-PUB, 2018
4. "Towards automated neutrino selection at MicroBooNE using tomorgraphic event reconstruction", MICROBOONE-NOTE-1040-PUB, 2018
5. Hunting muon neutrinos in microboone with deep learning techniques, MICROBOONE-NOTE-1051-PUB, 2018
6. "Reconstruction Performance Studies with MicroBooNE Data in Support of Summer 2018 Analyses", MICROBOONE-NOTE-1049-PUB, 2018
7. ""Detector Calibration using through going and stopping muons in the MicroBooNE LArTPC", MICROBOONE-NOTE-1048-PUB, 2018
8. Proton Track Identication in MicroBooNE Simulation for Neutral Current Elastic Events, MICROBOONE-NOTE-1025-PUB, 2017
9. "A Comparison of Monte-Carlo Simulations and Data from MicroBooNE", MICROBOONE-NOTE-1014-PUB, 2017
10. "Demonstration of 3D Shower Reconstruction on MicroBooNE Data", MICROBOONE-NOTE-1012-PUB, 2016

# Detector Physics results

NOW

## Publications

1. "*Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE*", arXiv:1804.02583, JINST 13, P07007 (2018)
2. *"Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation"*, arXiv:1802.08709, JINST 13, P07006 (2018)
3. *"Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC"*, arXiv:1705.07341, JINST 12, P08003 (2017)
4. *"Design and Construction of the MicroBooNE Detector"*, arxiv:1612.05824, JINST 12, P02017 (2017)

## Public Notes

1. "Study of Reconstructed $^{39}$Ar Beta Decays at the MicroBooNE Detector", MICROBOONE-NOTE-1050-PUB, 2018
2. *"A Measurement of the Attenuation of Drifting Electrons in the MicroBooNE LArTPC"*, MICROBOONE-NOTE-1026-PUB, (2017)
3. *"Establishing a Pure Sample of Side-Piercing Through-Going Cosmic-Ray Muons for LArTPC Calibration in MicroBooNE"*, MICROBOONE-NOTE-1028-PUB, (2017)
4. *"Study of Space Charge Effects in MicroBooNE"*, MICROBOONE-NOTE-1018-PUB, (2016)
5. *"A Method to Extract the Charge Distribution Arriving at the TPC Wire Planes in MicroBooNE", MICROBOONE-NOTE-1017-PUB, (2016)*
6. *"MicroBooNE Detector Stability"*, MICROBOONE-NOTE-1013-PUB, (2016)
7. *"Measurement of the Electronegative Contaminants and Drift Electron Lifetime in the MicroBooNE Experiment"*, MICROBOONE-NOTE-1003-PUB, (2016)
8. *"Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber"*, MICROBOONE-NOTE-1001-TECH , (2016)

# HEP portfolio Review

## Instructions for Proposers

- The proposal should address the following topics, which are closely related to, but not exactly the same as, the evaluation criteria:
  - **Overall scientific merit**, including that of the experiment itself, and its unique capabilities and relevance to the P5 science drivers as part of the overall HEP portfolio;
  - **Promise of future science impact** and productivity during this timeframe, including key science results expected, based on nominal experimental operations and demonstrated detector performance and capabilities;
  - **Impact of past scientific results** as evidenced by refereed publications, citations, etc.; and how these results relate to the projected precision of expected future science results;
  - **Accessibility, usability, and utility of the data**, both for the experiment itself and as a member of the broader HEP community, including working groups that combine and analyze data from multiple experiments; and quality and completeness of the data management plan including archiving and distribution;
  - **Productivity and vitality of the science team**, including continuity and expertise in the operation, calibration, and validation of instrumental data; scientific research productivity; and mentoring and training of younger scientists.

# Neutrino physics questions are at the forefront of particle physics today:

## Pursue the physics associated with Neutrino mass

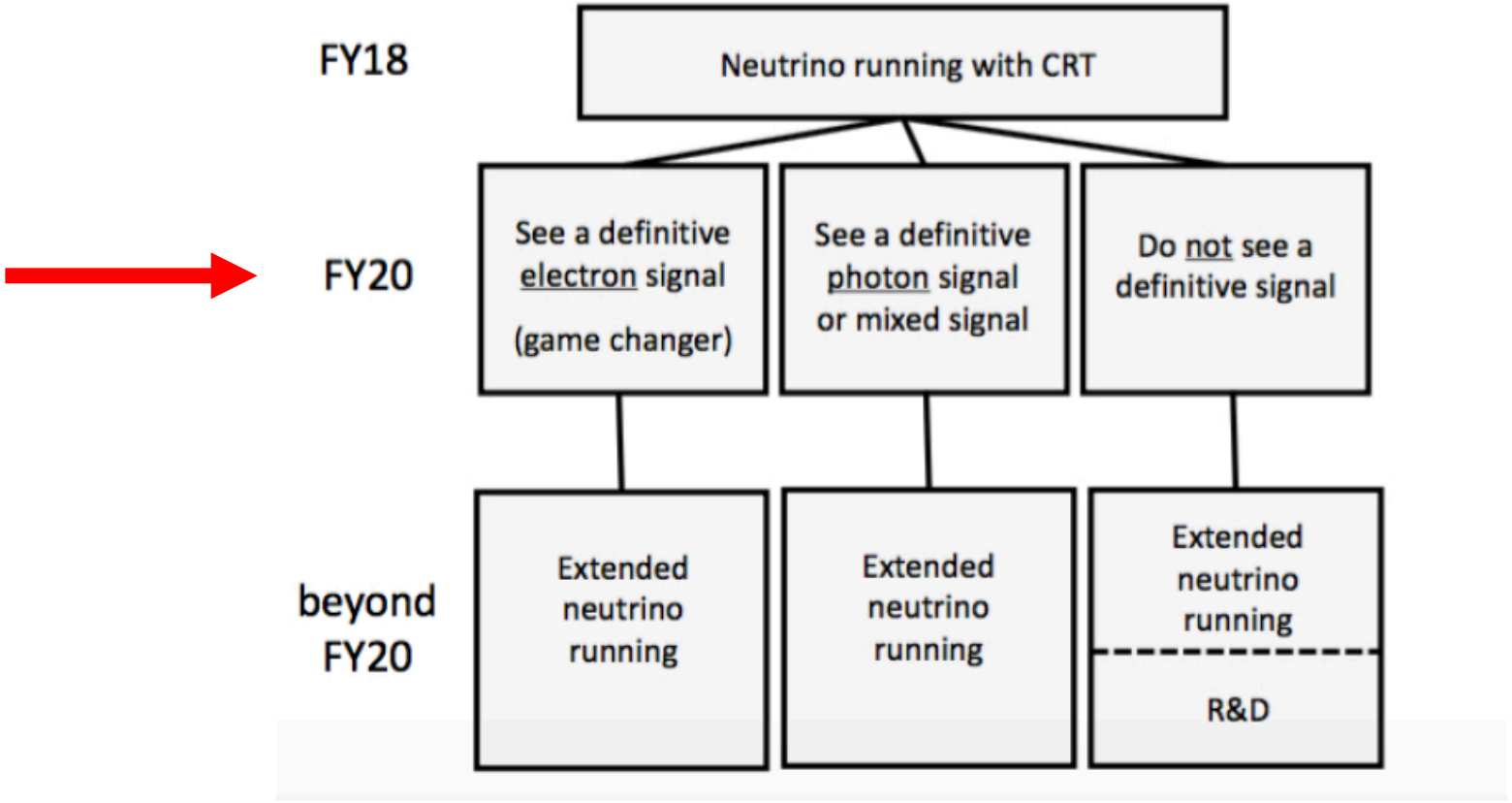
- Are there additional neutrino types or interactions?
  - (MicroBooNE Science)
- Do neutrinos and anti-neutrinos oscillate differently?
  - (MicroBooNE Technology → DUNE)

P5 Recommendation 15: "*Select and perform in the short term a set of small-scale experiments that can conclusively address experimental hints of physics beyond the three neutrino paradigm. Some of these experiments should use liquid argon to advance the technology an build the international community for DUNE at Fermilab.*"

# FY2020 Milestone

- Collected 13.2x$10^{20}$ POT overall (~10.5x$10^{20}$ with CRT)
- Complete approved run as SBND turns on
- Final oscillation analyses complete

→ guide us towards next steps



# Additional physics and technology goals and additional features of MicroBooNE Running

- Cross Sections, Astro-particle Physics and Exotics (APE)
  - MicroBooNE's 13.2 x $10^{20}$ POT will bring increased statistics for
    - High statistics cross section measurements (rare channels, Ph.D theses…)
    - Exotic searches for heavy sterile neutrinos, particles from the dark sector, trident signature searches
  - Extended running in time will enable
    - $n\bar{n}$ oscillation searches
    - Supernova neutrino burst searches
    - NuMI neutrino beam mmnts, relevant for DUNE (ICARUS, SBND will not take NuMI triggers).

- Detector physics:
  - Measurement of and corrections for space charge effects
  - Development of UV laser calibration system
  - Recombination/electron lifetime/diffusion measurements
  - Signal processing techniques
  - Cosmic tagging and removal
  - *High single PE rate*
  - *Cross connected channels*
  - *Raising the drift HV above -70kV*
- Additional features of Continued running:
  - Long term operation of the detector: Stability, ageing --> collecting lessons learned for SBN and DUNE
  - Platform for training young scientists in precision neutrino physics and specifically for LArTPCs

- Submitted written document to committee and presented to them in late February
- Report presented to HEPAP in May
- MicroBooNE requested change to the report as presented at HEPAP
  - Last sentence factually incorrect
  - Overall categorization based on this
- Other letters sent to Committee as well

*Original report: "Unfortunately, MicroBooNE has experienced technical problems that threaten its scientific impact and negatively affect the subpanel's overall evaluation. → Recommendation: Group 3"*

Report modified to change final sentence to:

*"The technical problems encountered by MicroBooNE threaten to lessen its scientific impact"*

No change in ranking

# Additional Letters to Committee (few excerpts)

- BERN colleagues: Antonio Ereditato

*"Last but not least we comment on specific international aspects. We are in the process of negotiations for a significant funding commitment to be made by the Swiss Confederation to the LBNF/DUNE facilities, like other international partners, which were already able to secure substantial funds. Any signals of lessened priority can have negative effects on these negotiations and thus for the whole US based neutrino program."*

- Steve Kettell (BNL):

*"While considering the challenges faced by the Portfolio Review committee, I believe that they have underestimated the importance of MicroBooNE to the US neutrino program. I am not a member of MicroBooNE, but have some reasonable understanding of it as several members of my group are active collaborators."*

- UK collaborators (Andrzej Szelc):

*"The HEPAP sub-panel evaluation creates a major risk for future UK and international funding. The perception is that HEPAP ranks the only major operating liquid-argon experiment in the US as low priority. We are currently undergoing a review of the UK particle-physics programme, and this negative evaluation could not have come at a worse time. It is particularly troubling that it seems to be based on a factually incorrect evaluation of the experiment's capabilities."*

# Discussions with DOE

- We (Sam and Bonnie) discussed with the DOE in early June: MicroBooNE future running, impact on International colleagues…

- Expecting formal response, for now, Glen responded in an email to share with our collaborators and with the PAC

**Crawford, Glen**

Inbox - Google 11:42 AM

Hide

GC

RE: MicroBooNE portfolio review outcome and trajectory

To: Bonnie Fleming,

Cc: Cooke, Michael, jim.siegrist@science.doe.gov <Jim.Siegrist@science.doe.gov>, Geralyn Zeller, Lykken, Joseph

Dear Bonnie,

I am writing to convey to you the results of recent DOE review of the MicroBooNE science program and the position of the DOE High Energy Physics program concerning additional MicroBooNE data-taking in the Fermilab Booster neutrino beam.

The recent HEPAP Portfolio Review ranked MicroBooNE in the 3rd tier of 13 currently operating HEP experiments, with their overall characterization being that such experiments "address the P5 drivers in important ways, but for which a reduction in funding would not cause irreparable harm to the DOE/HEP program."

The panel found that the MicroBooNE program combines useful physics goals with important technology development milestones, since it is pioneering the use of liquid Argon TPCs in a Fermilab experiment, and driving progress in understanding the optimization and limits of this technology. They further endorsed the originally planned experimental data-taking goal of 13.2 x 10**20 protons on target in order for MicroBooNE to provide definitive results on its signature physics measurements.

Our current understanding of the planned Fermilab facility operations schedule should allow MicroBooNE to achieve this goal in the first half of Fiscal Year 2020, with key physics results expected later in calendar 2020. Full analysis of the MicroBooNE dataset is expected to continue for another two years or so.

We concur with the panel's comments and plan to support continued MicroBooNE operations and analysis to achieve their initial physics goals in 2020 and complete analyses by approximately 2022. Any proposal for additional data-taking, or analysis of TPC technical and operational issues discovered during current data-taking, should be reviewed in the future by the Fermilab PAC following normal procedures.

These statements are in no way intended to negatively impact the standing of international partners or the collaboration. We appreciate that, given the timing and possible misinterpretations of the report recommendations, that some partners may be put in a difficult position. We stand ready to work with international partners who may have concerns about this outcome.

You may share this email with collaborators and the Fermilab PAC at your discretion. A more formal letter will follow.

Regards
Glen