

MicroBooNE update

for Fermilab PAC, Summer 2017

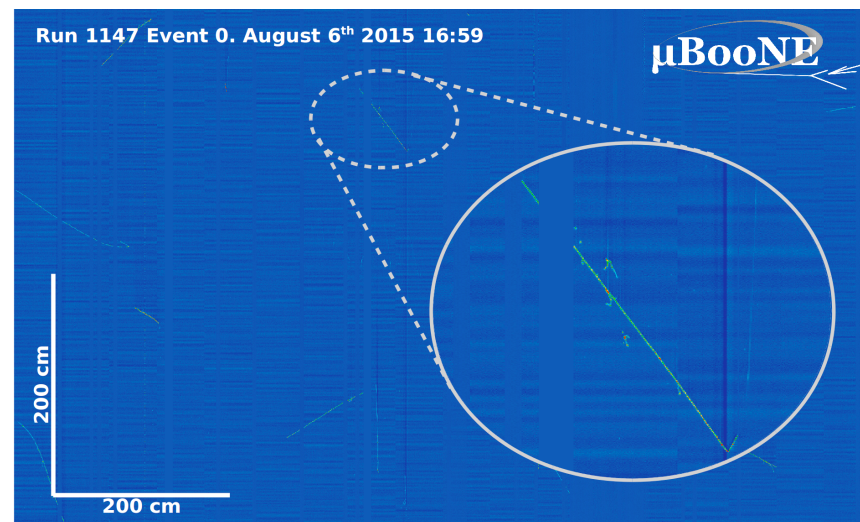
Bonnie Fleming on behalf of the
MicroBooNE Collaboration

MicroBooNE



- Goals:
 - address MiniBooNE LE excess
 - measure the first low energy neutrino-argon cross sections
 - R&D for future detectors (SBN and DUNE)
 - First phase in SBN program

- LAr TPC (170 tons)
 - Purity with non-evacuated argon fill
 - cold (in argon) front-end electronics
 - long drift distance (2.5 m)
 - near surface operation
 - UV laser calibration system
 - “Physics R&D”





MicroBooNE Collaboration

June 2017

University of Bern, Switzerland: **M. Auger**, **Y. Chen**, A. Ereditato, **D. Goeldi**, I. Kreslo, **D. Lorca**, **M. Lüethi**, **C. Rudolf von Rohr**, **J. Sinclair**, M. Weber

Brookhaven: M. Bishai, H. Chen, **J. Joshi**, **B. Kirby**, Y. Li, **M. Mooney**, X. Qian, V. Radeka, 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, **J. Zennamo**

University of Cincinnati: **R. Grosso**, R.A. Johnson, **J. St. John**

Columbia University: L. Camilleri, **D. Caratelli**, **D. Cianci**, **J. Crespo**, A. Fadeeva **V. Genty**, Y.-J. Jwa, **D. Kaleko**, G. Karagiorgi,

M. Ross-Lonergan, W. Seligman, M. Shaevitz, **K. Sutton**, **K. Terao**

Fermilab: B. Baller, F. Cavanna, **R. Castillo Fernandez**, G. Cerati, H. Greenlee, C. James, H. Jostlein, W. Ketchum, M. Kirby, T. Kobilarcik, S. Lockwitz, B. Lundberg, A. Marchionni, **S. Marcocci**, C. Moore, O. Palamara, Z. Pavlovic, S. Pordes, J.L. Raaf, A. Schukraft, E. Snider, P. Spentzouris, T. Strauss, M. Touns, S. Wolbers, T. Yang, **G.P. Zeller***

Illinois Institute of Technology: **R. An**, 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, G.B. Mills, R. Van de Water

University of Manchester: J. Evans, **A. Furmanski**, **D. Gamez**, **P. Guzowski**, **J. Hewes**, **C. Hill**, **R. Murrells**, **D. Porzio**, S. Söldner-Rembold, A.M. Szelc

MIT: J.M. Conrad, **G. Collin**, **A. Diaz**, **O. Hen**, **A. Hourlier**, **J. Moon**, **A. Papadopolou**, **T. Wongjirad**, **L. Yates**

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

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

Otterbein University: N. Tagg

University of Oxford: G. Barr, **M. Bass**, **M. Del Tutto**, R. Guenette, **A. Laube**, **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, **B. Eberly**, L. Rochester, **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

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Tubitak Space Technologies Research Institute, Turkey: F. Bay, **B. Kocaman**, **M. Kopru**

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

Yale University: **C. Adams**, **S. Balasubramanian**, **B.T. Fleming***, **E. Gramellini**, **A. Hackenburg**, **X. Luo**, **B. Russell**, **L. Cooper-Troendle**, **S. Tufanli**

170 collaborators

28 institutions (7 non-U.S.)

39 postdocs

53 graduate students

*spokespeople

PAC Charge

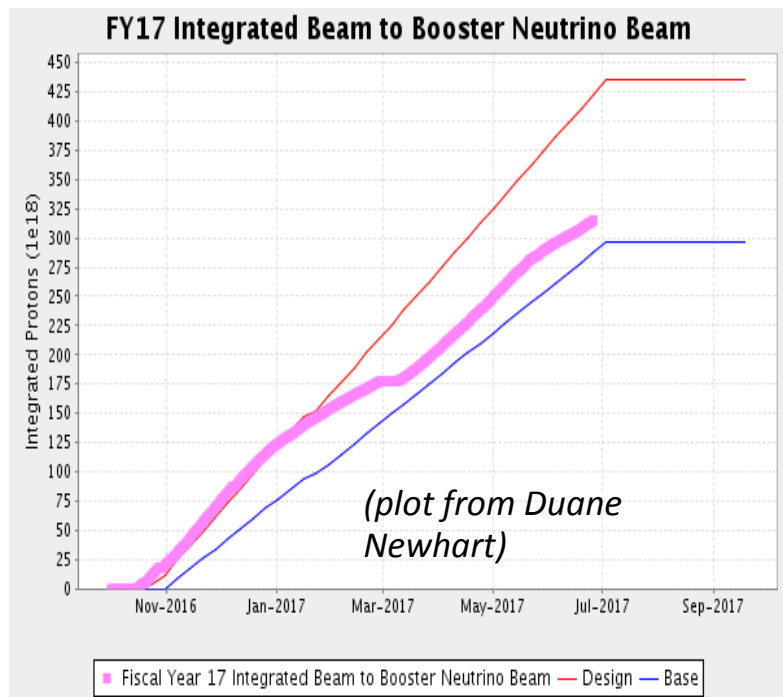
2. MicroBooNE: Lessons learned & FY18 Running

- i) The initial MicroBooNE request for $6.6E20$ POT has almost been fulfilled. The experiment is also approved for an additional $6.6E20$ POT in the “SBN era.” It was initially thought that this additional running would be coincident with the other SBN-experiment running. However, the BNB has performed sufficiently well to enable the initial request to be completed one year ahead of schedule. MicroBooNE is requesting continued running in FY18. We ask the committee to comment on the MicroBooNE plan for FY18 and beyond keeping in mind the goals of the experiment
- ii) We ask the committee to comment on the lessons learned from MicroBooNE to date and the plans to ensure effective utilization of the experience gained, keeping in mind that one of the motivations for the MicroBooNE experiment is to provide experience and information that will help prepare for the LBNF/DUNE era.

plus some of your questions along the way...

Continued running in FY2018....

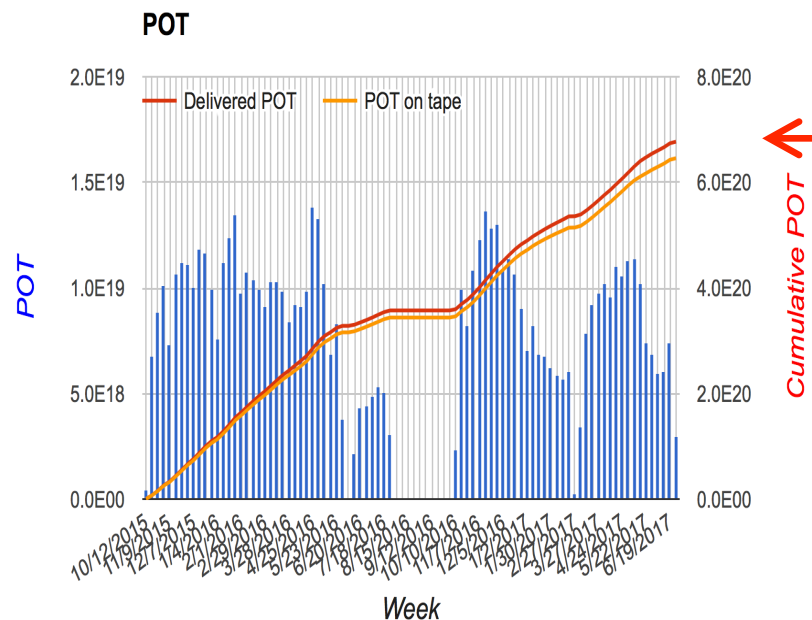
- By end of FY2017 we will have collected $6.1\text{E}20$ POT
- Completion of initial $6.6\text{E}20$ POT run by January 2018



Beam Delivery to MicroBooNE

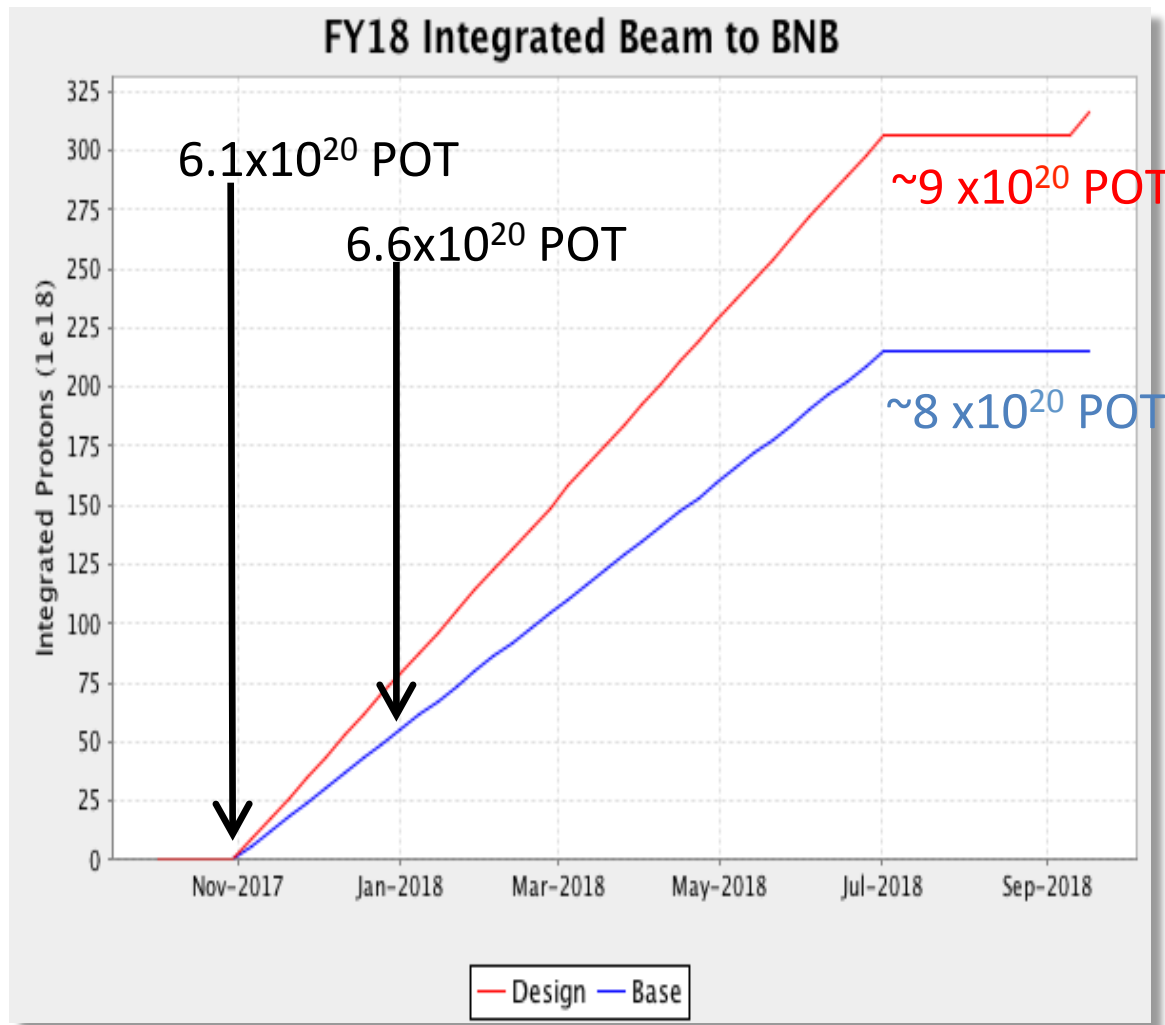
beam delivery in FY17

beam delivery since start of uB operations



expect to have collected
 6.1×10^{20} POT
 (uB detector on, on-tape)
 by the start of the 2017
 summer shutdown

Beam Projections in FY18



- should get to **6.6x10²⁰ POT** of BNB (initial beam request) in **January 2018**
- expect an additional **~(1.5-2.5) x 10²⁰ POT** of BNB beyond this before the 2018 summer shutdown for a grand total of

~8 x10²⁰ POT (base)

~9 x10²⁰ POT (design)

to uB by July 2018

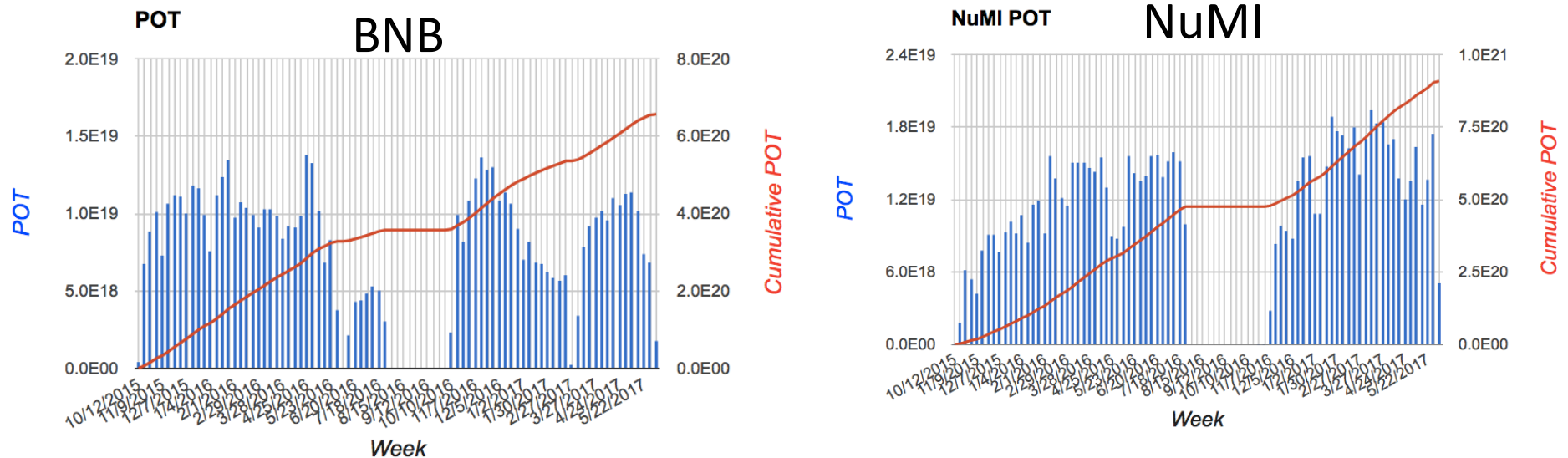
(plot from Mary Convery)

Continued running in FY2018....

- By end of FY2017 we will have collected $6.1\text{E}20$ POT
- Completion of initial $6.6\text{E}20$ POT run by January 2018
- Begin “SBN era” $6.6\text{E}20$ POT run immediately after this to be completed in ~ 2 years
 - Complete this run as soon as possible – beam is available, detector is operational, team is working \rightarrow take the data....
 - Some overlap with ICARUS running in late FY2018, FY2019
 - Running beyond $13.2\text{E}20$ POT (into FY2020) will depend on results of signature analysis.

Status of running over the past year....

Operations, New detector functionality, Analysis



→ >95% average uptime collecting data: running well

→ Two significant downtimes:

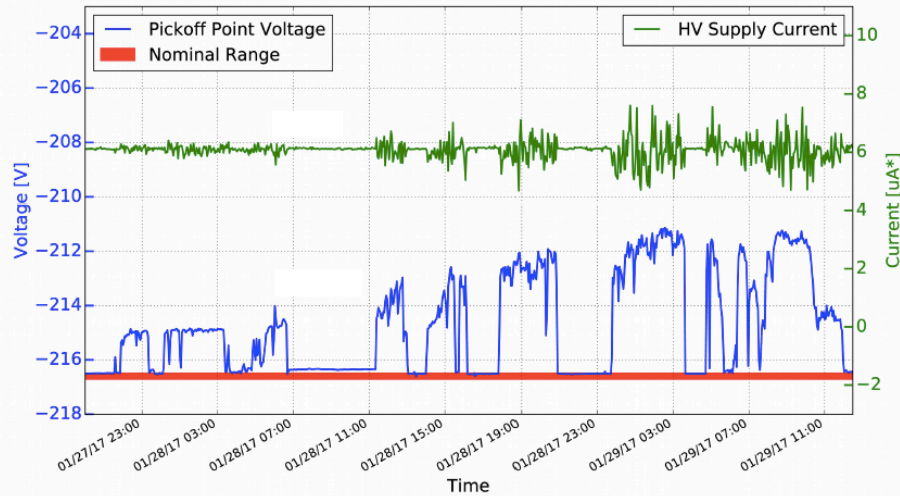
- 28 days in Feb → Connection at HV feedthrough
- 14 days in May → consequence of problems coming up from power outage

→ Implemented several detector upgrades

Lessons learned
New techniques developed

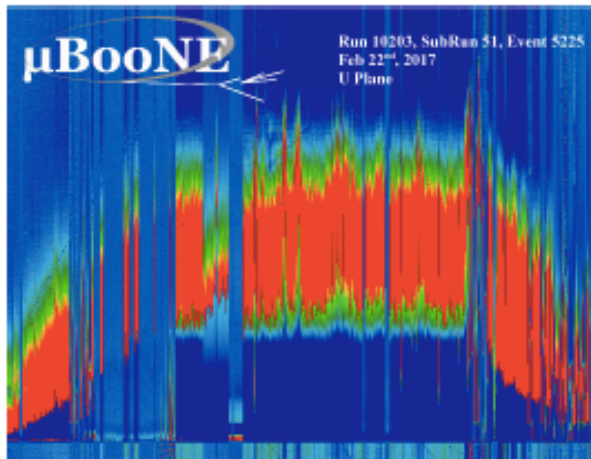
Downtime in February....

Large variations in pick-off point at anode
and at HV supply, increased noise levels on
readout channels



- Symptoms pointed to several different possible causes
- Systematically checked all possible causes starting from least risky and moving to more risky. Worked carefully to avoid damaging detector in the process.
- Observed light in connection with burst events
- Along the way developed new techniques for using the cathode as a diagnostic tool (*Paper in preparation*) *Lesson learned...*
- Verified robustness of front end elec.

Events associated with activity



MANY THANKS TO MANY PEOPLE AT FNAL FOR HELP!

Solution: Transients on the cathode causing all anomalies

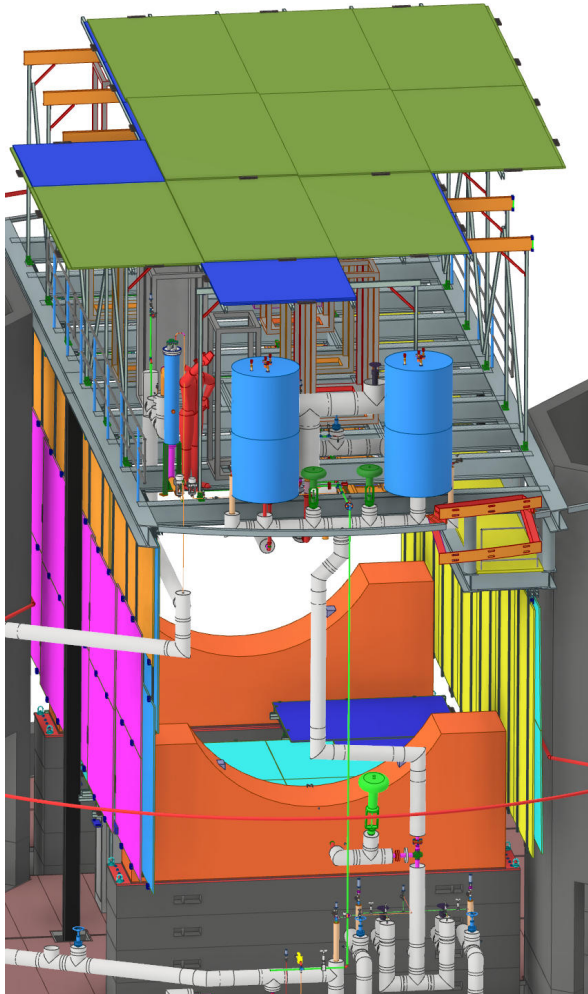
- Adjust HV connection between feedthrough and cup inside the TPC (removed iceball and adjusted bellows)
- All symptoms corrected immediately



Status of running over the past year....
*Operations, **New detector functionality**, Analysis*

- Service Board replacement: October 2016: → low voltage regulators on front-end ASICs → improve signal/noise by x2-3. Further noise reduction achieved using offline filter
- Installed second HV filter pot: October 2016 → fixed odd harmonics of 36kHz
- Enabled Supernova stream capability: January 2017
- Installed full Cosmic Ray Tagger (CRT): March 2017
- Enabled Heavy sterile neutrino trigger: June 2017

Cosmic Ray Tagger System



MicroBooNE Cosmic Ray
Tagger scheme

- Plastic scintillator modules - SiPMs readout
- 73 modules in 4 planes surrounding the cryostat
- 85% coverage for crossing muons

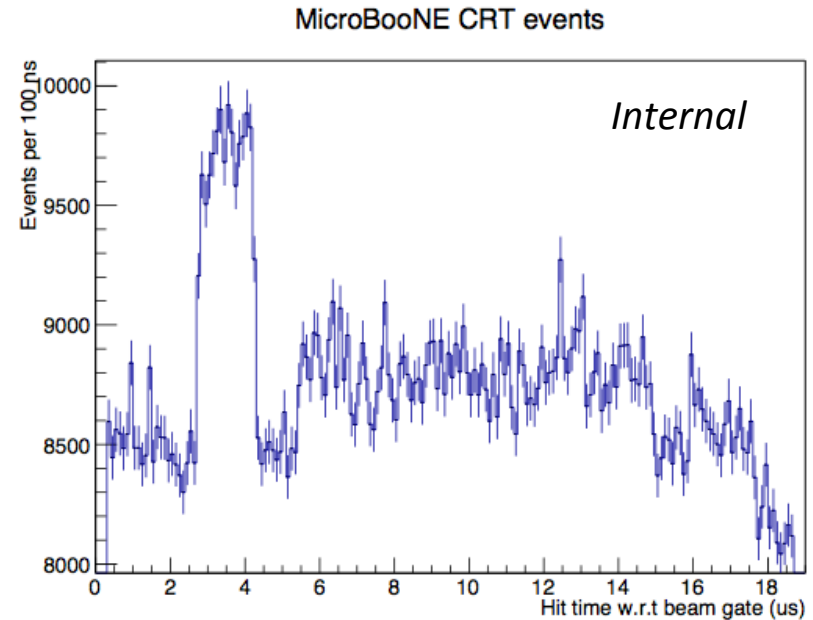
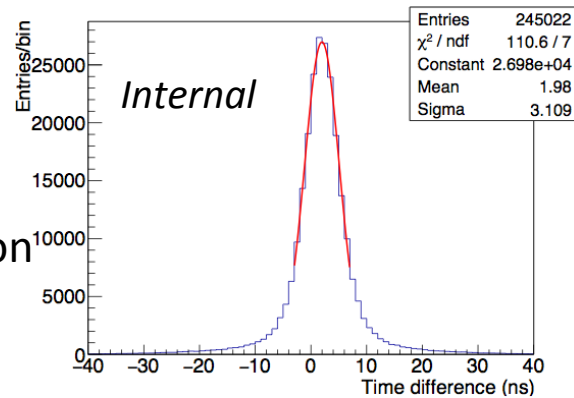
Installation and
commissioning
completed in
March 2017.



CRT Performance

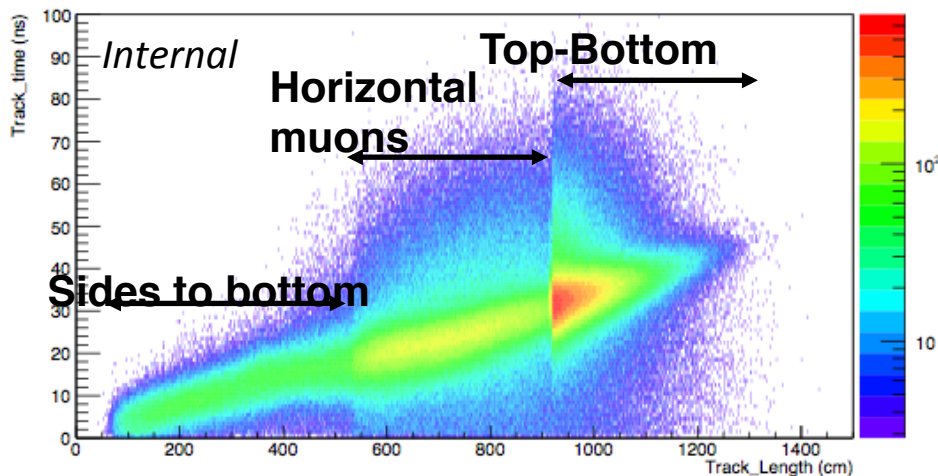
Time difference
for two adjacent
modules

Timing information
Resolution ~ 3 ns
RMS



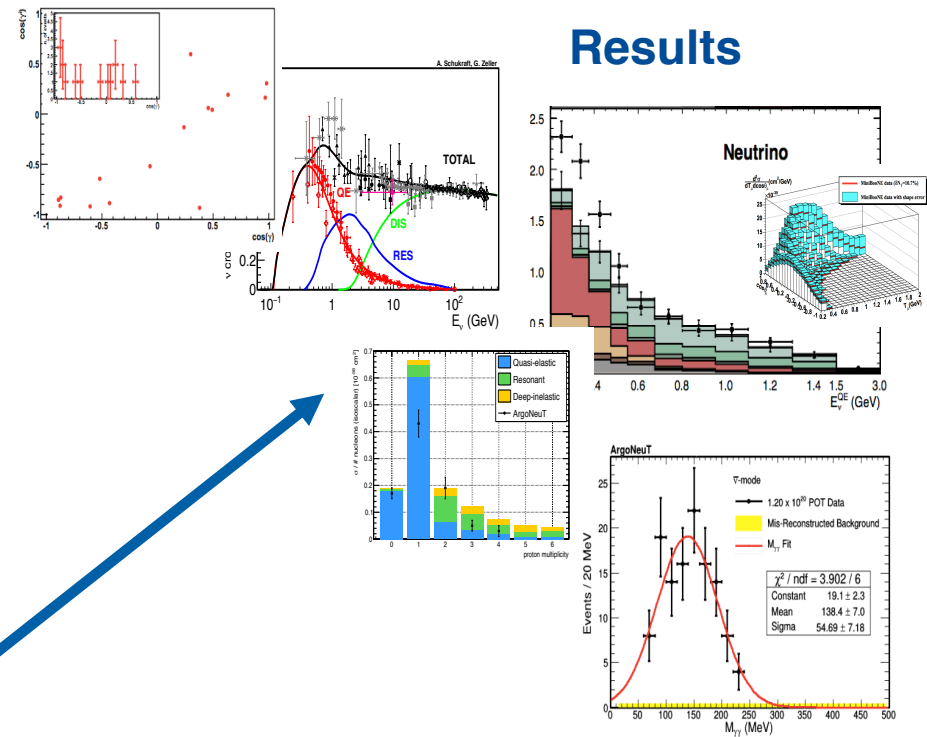
BNB & NuMi related muons time
distribution

CRT Tracks distribution



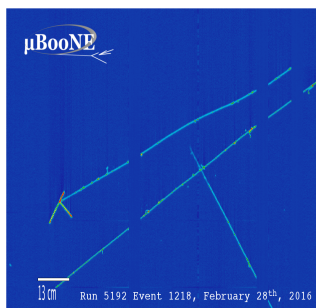
- CRT is fully installed
- will provide crucial input in removing cosmics in our neutrino analyses
- Will enable detector calibration/detector physics studies
- SBN installation smooth with experience from MicroBooNE
- Major International contribution
→ first major system delivered in ND

How do we get there?



Results

Data



Status of running over the past year....
*Operations, New detector functionality, **Analysis***

Anne Schukraft
 FNAL User's meeting, 2017



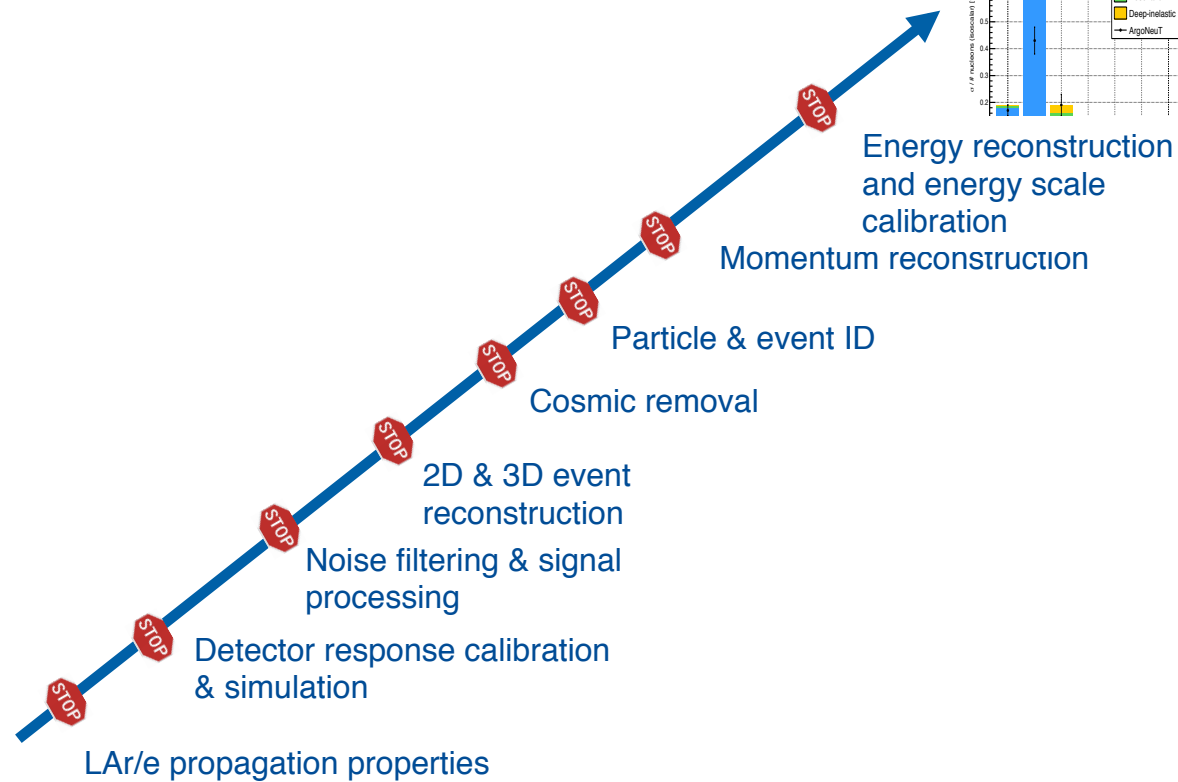
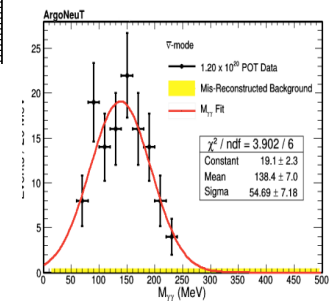
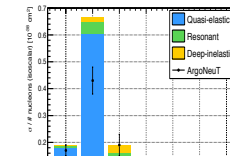
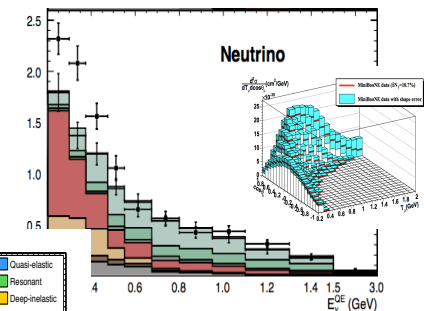
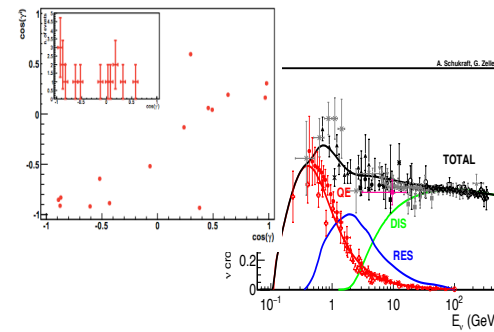
7/06/17

MicroBooNE update for PAC, Summer 2017

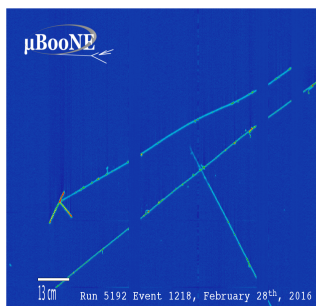
14



Results

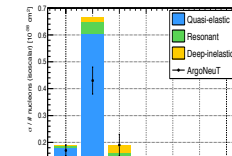
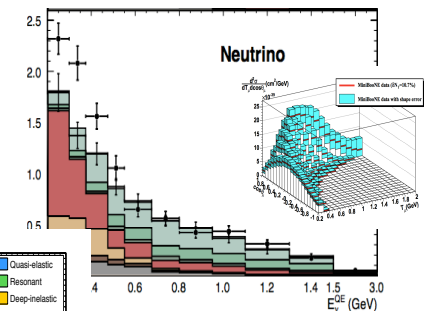
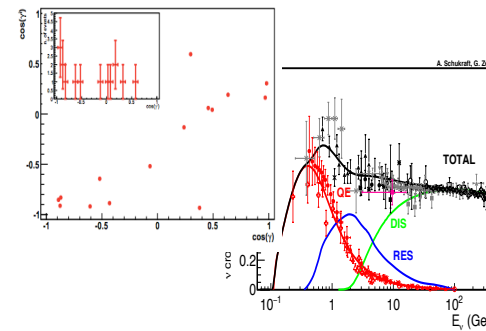


Data



Publications

Results



Energy reconstruction
and energy scale
calibration

Momentum reconstruction

Particle & event ID

Cosmic removal

2D & 3D event
reconstruction

Noise filtering & signal
processing

Detector response
calibration & simulation

LAr/e propagation properties

*Design and Construction of the
MicroBooNE Detector;*
[arXiv:1612.05824](https://arxiv.org/abs/1612.05824)

*Noise Characterization and Filtering in
the MicroBooNE Liquid Argon TPC;*
[arXiv:1705.07341](https://arxiv.org/abs/1705.07341)

*Convolutional Neural Networks Applied to
Neutrino Events in a Liquid Argon Time Projection
Chamber;* [arXiv:1611.05531](https://arxiv.org/abs/1611.05531)

*The Pandora multi-algorithm approach to
automated pattern recognition of cosmic-
ray muon and neutrino events in the
MicroBooNE detector; coming soon*

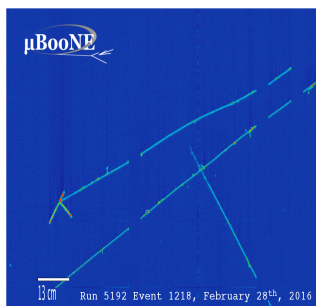
Anne Schukraft
FNAL User's meeting, 2017

*Measurement of cosmic-ray reconstruction
efficiencies in MicroBooNE using a small external
cosmic-ray counter; coming soon*

*Determination of muon momentum in the MicroBooNE
LAR TPC using an improved model of multiple Coulomb
scattering;* [arXiv:1703.06187](https://arxiv.org/abs/1703.06187)

*Michel Electron Reconstruction Using
Cosmic-Ray Data from the MicroBooNE
LAR TPC;* [arXiv:1704.02927](https://arxiv.org/abs/1704.02927)

Data



7/06/17

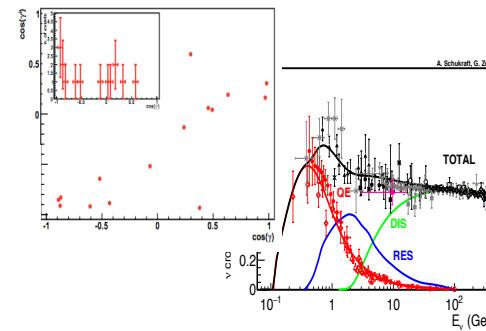
MicroBooNE update for PAC, Summer 2017

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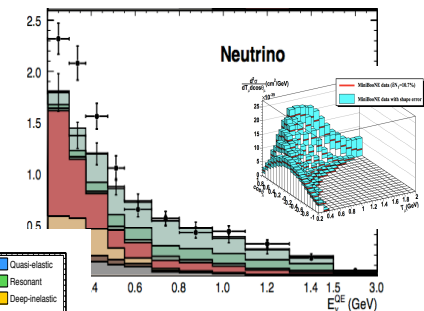
Short Baseline Neutrino

Public notes

<http://www-microboone.fnal.gov/publications/publicnotes/>



Results



Michel Electron Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC; [arXiv:1704.02927](https://arxiv.org/abs/1704.02927)

Determination of muon momentum in the MicroBooNE LArTPC using an improved model of multiple Coulomb scattering; [arXiv:1703.06187](https://arxiv.org/abs/1703.06187)

Energy reconstruction and energy scale calibration

Track multiplicities

Momentum reconstruction

CC muon kinematics
Particle & event ID
Proton ID

Cosmic removal

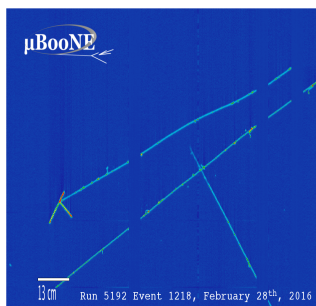
Cosmic shielding studies
2D & 3D event reconstruction

Noise filtering & signal processing

Charge extraction
Detector stability studies
Detector response calibration & simulation

Space charge studies
LAr/e propagation properties

Data



Design and Construction of the MicroBooNE Detector; [arXiv:1612.05824](https://arxiv.org/abs/1612.05824)

Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC; [arXiv:1705.07341](https://arxiv.org/abs/1705.07341)

[~ since last year's User's meeting]

Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber; [arXiv:1611.05531](https://arxiv.org/abs/1611.05531)
The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector; coming soon

Anne Schukraft
FNAL User's meeting, 2017



7/06/17

MicroBooNE update for PAC, Summer 2017

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Short Baseline Neutrino

MicroBooNE Physics

- MicroBooNE has been producing a steady stream of output ...
- **6 papers this year with more coming**
 - “Measurement of Cosmic Ray Reconstruction Efficiencies Using a Small External Cosmic Ray Counter”, *arXiv:17xx.xxxx*
 - “Noise Characterization and Filtering in the MicroBooNE LAr TPC”, *arXiv:1705.07341*
 - “Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC”, *arXiv:1704.02927*
 - “Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering”, *arXiv:1703.06187*
 - “Convolutional Neural Networks Applied to Neutrino Events in a LAr TPC”, *JINST 12, P03011 (2017)*
 - “Design and Construction of the MicroBooNE Detector”, *JINST 12, P02017 (2017)*
- **15 public notes**
 - describing detector performance, reconstruction techniques, and initial physics analyses

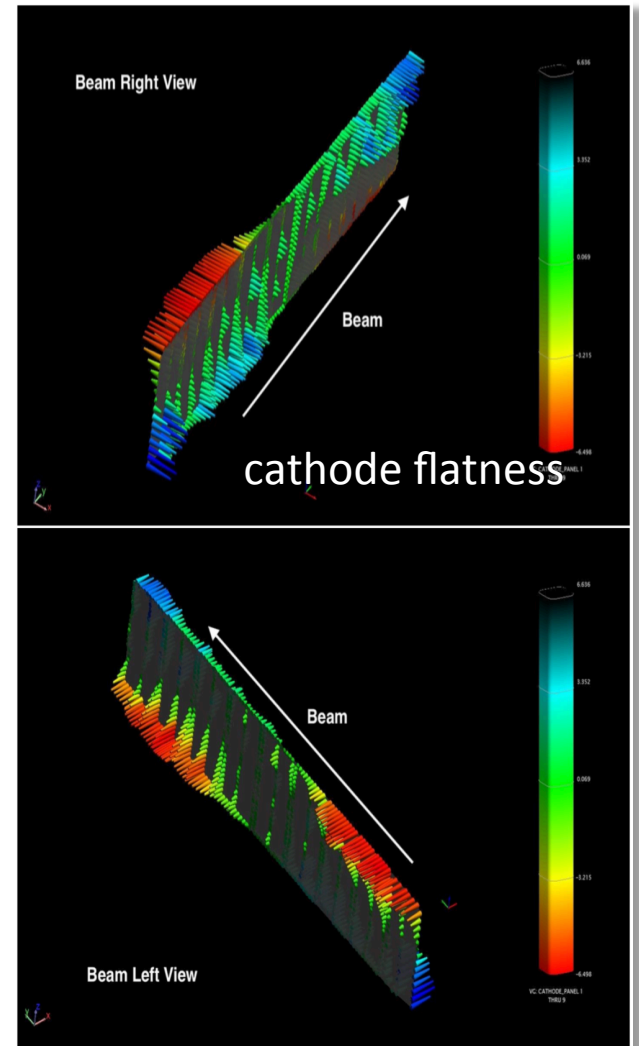
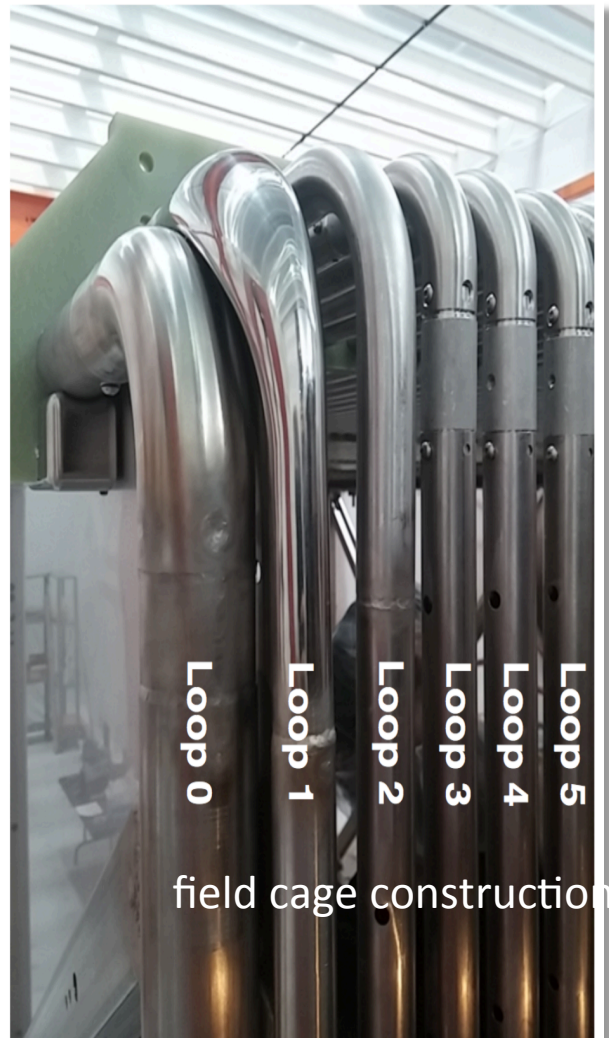
<http://www-microboone.fnal.gov/publications/publicnotes>

Public Notes:

- ♦ 6/4/17 [MICROBOONE-NOTE-1024-PUB](#)
Measurement of Reconstructed Charged Particle Multiplicities of Neutrino Interactions in MicroBooNE
- ♦ 1/26/17 [MICROBOONE-NOTE-1025-PUB](#)
Proton Track Identification in MicroBooNE Simulation for Neutral Current Elastic Events
- ♦ 11/29/16 [MICROBOONE-NOTE-1018-PUB](#)
Study of Space Charge Effects in MicroBooNE
- ♦ 7/4/16 [MICROBOONE-NOTE-1017-PUB](#)
A Method to Extract the Charge Distribution Arriving at the TPC Wire Planes in MicroBooNE
- ♦ 7/4/16 [MICROBOONE-NOTE-1015-PUB](#)
The Pandora multi-algorithm approach to automated pattern recognition in LAr TPC detectors
- ♦ 7/4/16 [MICROBOONE-NOTE-1014-PUB](#)
A Comparison of Monte-Carlo Simulations and Data from MicroBooNE
- ♦ 7/4/16 [MICROBOONE-NOTE-1013-PUB](#)
MicroBooNE Detector Stability
- ♦ 7/4/16 [MICROBOONE-NOTE-1012-PUB](#)
Demonstration of 3D Shower Reconstruction on MicroBooNE Data
- ♦ 7/4/16 [MICROBOONE-NOTE-1010-PUB](#)
Selection and kinematic properties of numu charged-current inclusive events in 5E19 POT of MicroBooNE data
- ♦ 5/3/16 [MICROBOONE-NOTE-1006-PUB](#)
Study Towards an Event Selection for Neutral Current Inclusive Single π^0 Production in MicroBooNE
- ♦ 5/30/16 [MICROBOONE-NOTE-1005-PUB](#)
Cosmic Shielding Studies at MicroBooNE
- ♦ 11/6/15 [MICROBOONE-NOTE-1004-PUB](#)
MC performance study for an early numu charged-current inclusive analysis with MicroBooNE
- ♦ 5/29/16 [MICROBOONE-NOTE-1003-PUB](#)
Measurement of the Electronegative Contaminants and Drift Electron Lifetime in the MicroBooNE Experiment
- ♦ 11/2/15 [MICROBOONE-NOTE-1002-PUB](#)
First neutrino interactions observed with the MicroBooNE Liquid-Argon TPC detector
- ♦ 8/28/15 [MICROBOONE-NOTE-1001-TECH](#)
Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber

MicroBooNE Detector

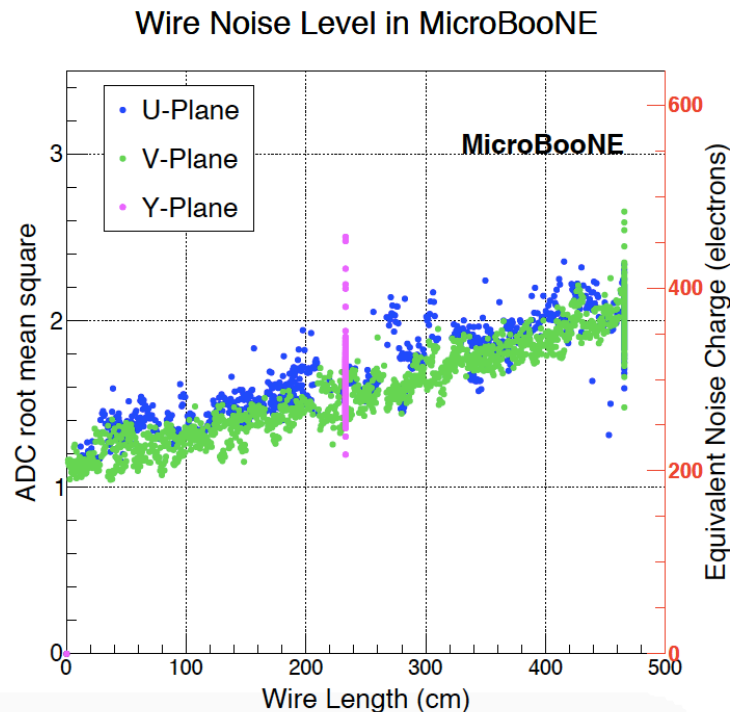
- 100+ page paper detailing design and construction of the MicroBooNE detector
- important resource (*ICARUS detector paper has been cited >300 times*)



R. Accarri *et al*, JINST, 12, P02017 (2017)

Noise Characterization & Mitigation

- comprehensive paper characterizing noise sources in the MicroBooNE TPC (*sources: drift HV power supply, LV regulators on front-end ASICs, wire motion, 900 kHz burst noise*)



- ENC is < 400 electrons for longest wires (4.7 m), consistent with design expectations. Noise level is significantly lower than previous experiments using warm front-end electronics.

R. Accarri *et al*, arXiv:1705.07341, submitted to JINST

Noise

It will be useful to compare the stated requirements and specifications for the readout electronics in terms of electron-equivalent noise and the HHV feedthrough for the drift field at the time of the CD3 TDR and to understand the differences and their impact on physics results.

The MicroBooNE CD3 requirement was an electron equivalent noise of < 660 ENC (Section 3.5 of <https://www-microboone.fnal.gov/publications/TDRCD3.pdf>). After our software noise filtering, we measure < 400 ENC for all "good" wires (Figure 16 in <https://arxiv.org/abs/1705.07341>). Along with a high electron lifetime, this gives us the ability to run at lower drift field without compromising our physics goals.

- ***CD3 requirement: < 660 ENC***
- ***Test stand measurement: ~ 500 ENC (1us peaking time, 150 pF capacitance, in cold)***
- ***Actual: < 400 ENC***

Noise

It will be useful to understand further the ASIC channel misconfiguration and shorted wire issue. How many wires were impacted by each problem and where are they? Was it possible to reproduce and fully understand the origin of this issue? Depending on the possible origin of this issue, are there strategies to avoid them in the future?

Misconfigured channels: *Roughly 400 channels were misconfigured up through the start of summer 2016 and 300 channels became misconfigured after that. These are usable channels with real signal – they effectively have more ENC noise. We believe this issue is related to electrostatic discharge on the cold motherboards, leading to the ASICs being stuck in this state. This has been addressed in subsequent ASIC designs with more robust electrostatic discharge protection on the configuration pins.*

Connected channels: *Approximately 400 channels are affected in a particular region of the detector (this is what makes up most of the total dead channel count). The impact is a distortion in the local electric field. We are working on methods to perform signal recovery in these region. We looked inside the detector (<https://arxiv.org/abs/1507.02508>) and do not see physical evidence for physically touching wires. However, spacers have been added in the SBND and DUNE designs to reduce wire vibrations (for example, new support combs in SBND ensure that the unsupported wire length is no more than ~ 1.5 m).*

Noise

It will be useful to understand further the issue of saturation in the readout. What is the frequency and duration of the saturation, and what is the expected average number and location of channels affected during beam events?

***Saturation** varies at a rate of 1-10 Hz and impacts some V (middle) plane wires. The average number of impacted channels per event, weighted wrt dead time, is $O(10)$ channels with our nominal leakage current setting of 500 pA. These channels are automatically identified on an event-by-event basis and are taken into account in the subsequent reconstruction chain. Next generation of ASICs now have additional input bias current settings in response to this.*

Noise

It will be useful to understand for each source of excess noise its origin and remediation.

See paper (<https://arxiv.org/abs/1705.07341>) for more details. To summarize:

- **Low-frequency (< 30 kHz) coherent noise:** currently understood as being an oscillation in the ASIC power line involving the voltage regulator; ameliorated by replacing voltage regulators on service boards in summer 2016.
- **Harmonic noise:** due to drift HV power supply switching (~36 kHz); largest effect seen on the U plane (is closest to the cathode); eliminated by installing a second drift HV filter pot in summer 2016.
- **“Zig-zag” high-frequency (~900 kHz) pick-up noise:** impacts U/V plane wires at the downstream end of the TPC; current source is unknown but is being investigated in more detail this summer; does not impact data analysis as it is removed offline with a low-pass software filter.
- **Purity monitor induced noise:** activation of the in-vessel purity monitors causes enough light to be produced within the cryostat that the PMTs see a burst of light causing a large induced signal on the closest TPC wires; < 0.2% of events saw this noise before the purity monitors were permanently disabled in May 2016.

Noise

It will be useful to detail the impact of noise and channel disabling on exposure: what is the expected equivalent loss of POT due to unmitigated excess noise and channels disabling due to different sources?

We estimate a 3% inefficiency (or equivalent loss in POT) with 2 out of 3 plane reconstruction. More detailed studies on the impact on event reconstruction is under investigation.

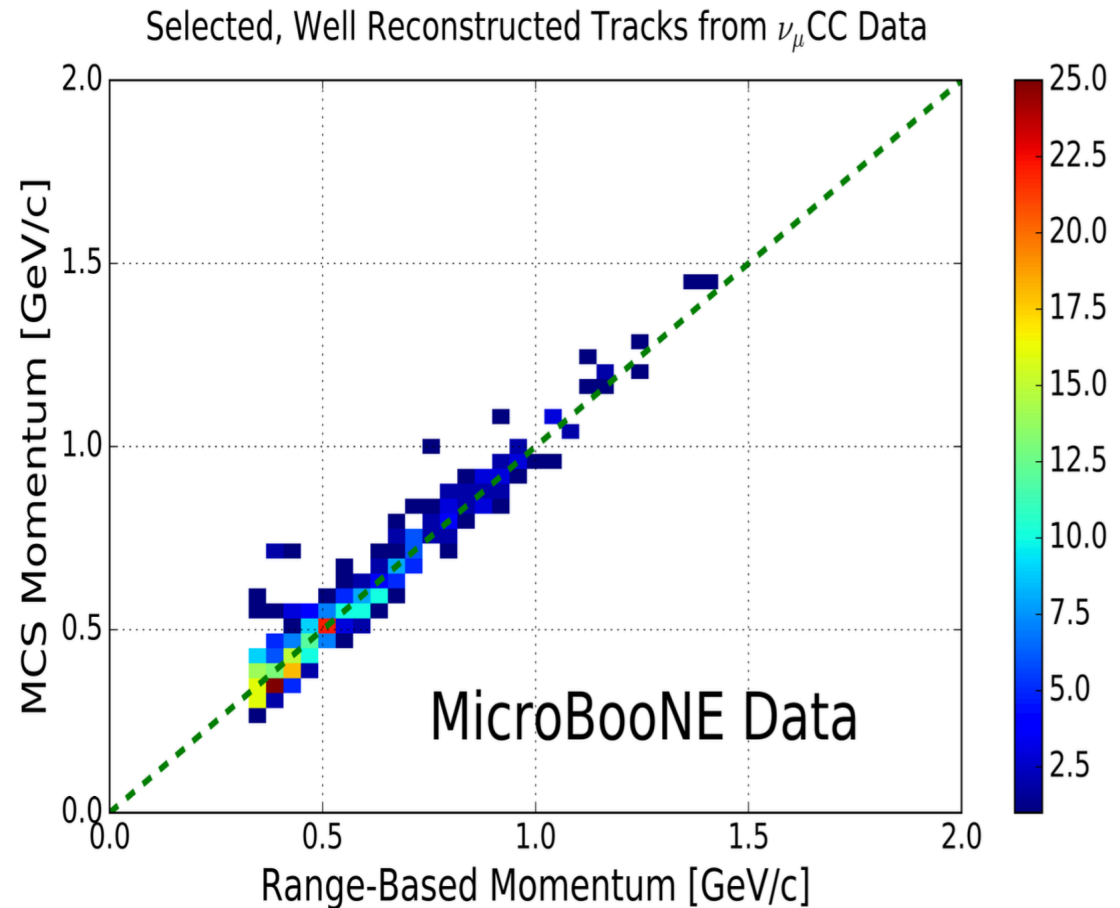
Impact of MicroBooNE Noise Studies

- **ASIC saturation:** new generation ASICs now have additional input bias current settings
- **Wire vibrations:** spacers have been added to support the anode wires in the design of new LAr TPCs to reduce vibrations and wire motion from fluid flow
- **Misconfigured channels:** additional electrostatic discharge protection has been added on the configuration pins in next generation ASICs
- **ASIC startup:** design margin of the bandgap reference circuit has been increased in the new ASIC design to remove start-up problems
- **Electronics environment:** additional attention is being paid to grounding during building construction (e.g., SBND, ICARUS); current monitoring
- **Offline noise filtering:** MicroBooNE approach and code had immediate impact on DUNE 35 ton data analysis

R. Accarri *et al*, arXiv:1705.07341, submitted to JINST

Muon Momentum Reconstruction

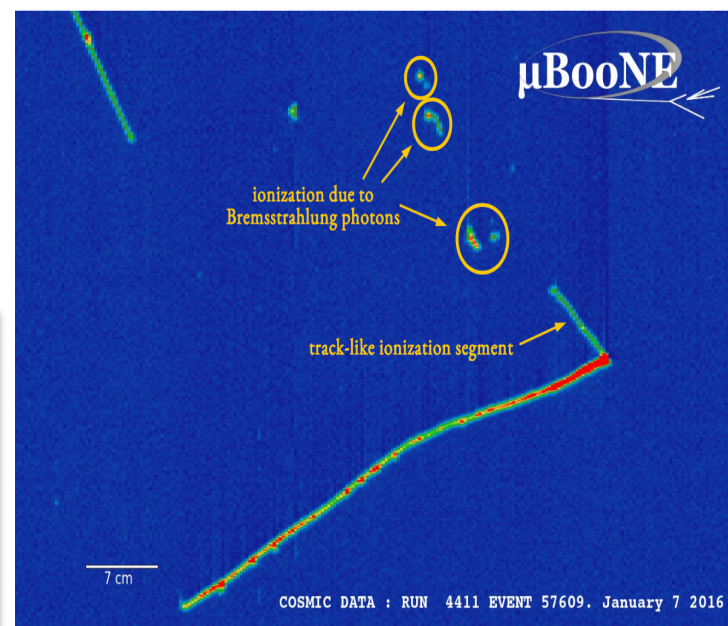
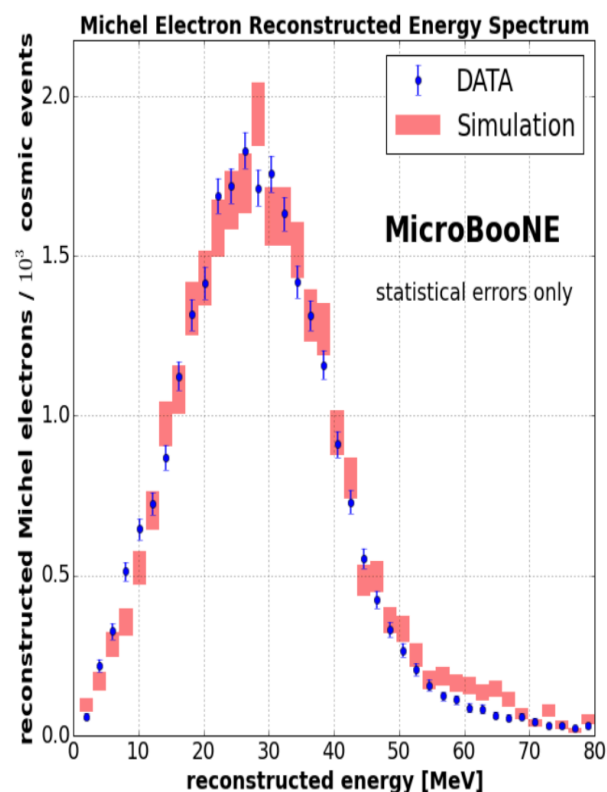
- measurement of muon momentum using multiple coulomb scattering in ν_μ CC interactions using 3D reconstructed muon tracks
- important for exiting muons (many of muons in μB)



R. Accarri *et al*, arXiv:1703.06187, submitted to JINST

Michel Electron Reconstruction

- largest sample of Michel electrons ever reconstructed in a LAr TPC (~14k)
- fully automated identification and reconstruction (2D)
- important step towards better understanding e^- reconstruction and energy resolution



R. Accarri *et al*,
arXiv:1704.02927,
submitted to JINST

Michel Electrons

The value of the energy resolution (20%) is very surprising at first glance. It would be useful to clarify and add a discussion that the resolution obtained by this study is not a fair determination of the resolution for signal events in LAr (neither in your experiment nor in DUNE in the future). This discussion will probably need to include the micro-details of all the difficulties you have removing the Bragg peak (all the background you mention and probably secondary sources such as photons arising from the muon that gave rise to the electron - this muon will also have delta-rays which will also make photons etc.). Further to this a very important question is what study can demonstrate the best resolution you can achieve? Do you have any feel what the best resolution value will be? Also, what is the worst resolution you can afford while still being able to carry out your primary physics goal(s)?

In the paper, we have not asserted that the resolution obtained in this analysis is a determination of the resolution for signal events in SBN or DUNE. We do not attempt such an extrapolation. This analysis is a first step in learning what matters most for EM shower energy reconstruction in LAr TPCs using actual data, and is guiding us in improving our reconstruction. As an example, the "challenge" of clustering low energy electromagnetic activity was not something widely discussed before we started this work.

We need to complete our detector calibration program before making firm quantitative statements about achievable energy resolution and its impact on our physics measurements. We are also working on a π^0 analysis and expect improvements in Michel reconstruction when this analysis is repeated in 3D. We believe that the 20% result obtained for Michel electrons is an upper limit on the expected energy resolution - at higher energies, the impact of hit thresholds and clustering should become smaller.

Michel Electrons

The Michel electron sample is 80-90% pure with background “dominated by EM activity produced by cosmic-ray muons from delta-rays or bremsstrahlung photons”. It would be useful to see what this looks like in the MC (broken down in all components).

Backgrounds were studied by visually inspecting both data and MC events and were found to mostly consist of tagged EM activity from muons (delta-rays or bremsstrahlung photons) when such activity occurred close to the beginning or end of a muon track. A smaller subset of background events consisted of muon tracks which had undergone a large angle scatter. More detail on this has been added in a later version of the Michel paper.

We did not attempt to quantify the breakdown in the MC, partially because this is technically challenging to do on cosmic events. For each event, hundreds of EM interactions occur at ~ 10 's of MeV energy. Identifying the source of the mis-ID case-by-case and agreeing to a method to do so is not trivial.

Michel Electrons

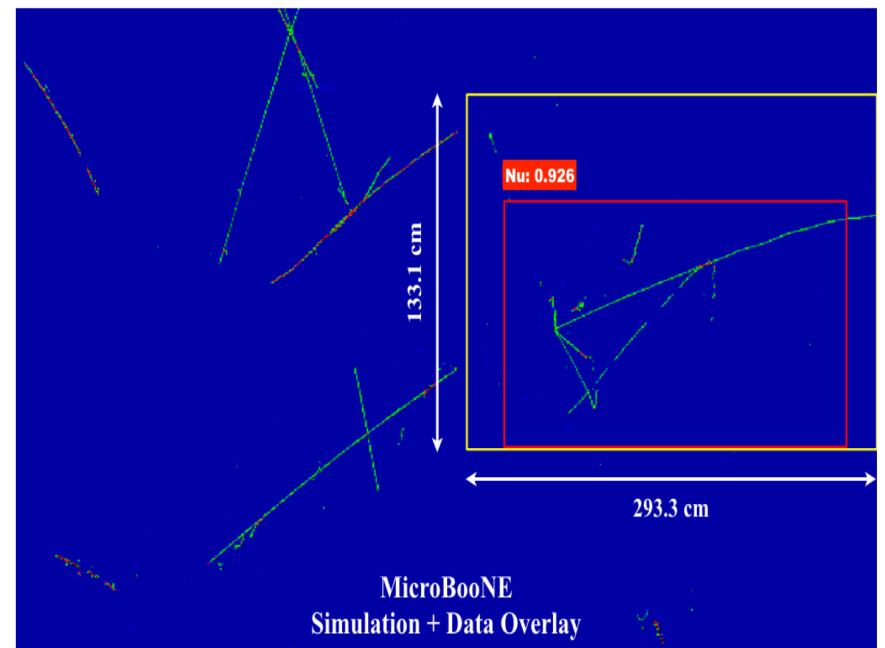
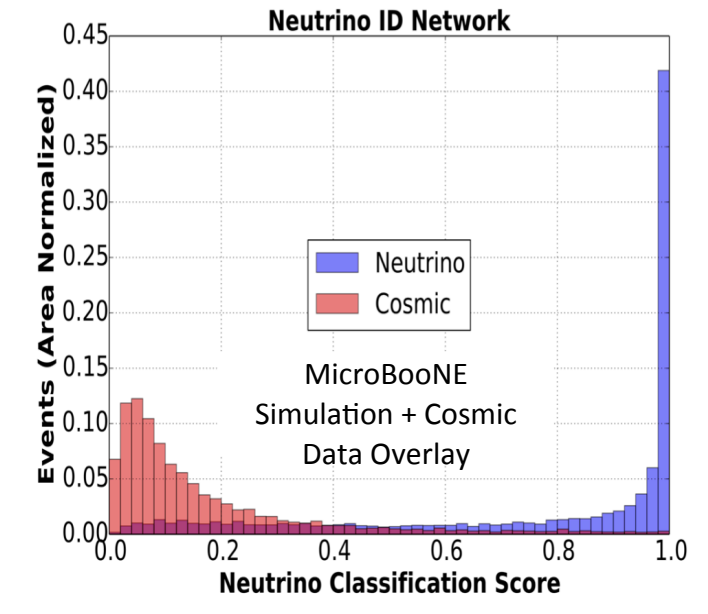
The cosmic rays in the data appear to be obstructing your ability to collect the energy from emitted photons. It also appears that this could not be completely mitigated by placing the detector underground given the 1 MeV detector design threshold that misses most of the photons and 15% of the photon energy as discussed in the paper. Some useful future studies you might want to launch include the quantification of i) improvement expected by placing the detector underground ii) achievable improvement by lowering the 1 MeV threshold iii) possible design change to be able to do a much lower threshold if it was deemed important enough.

It is too soon to say that a ~ 1 MeV threshold is the best we can ever do, based on this initial Michel analysis. The 1 MeV threshold was dominated by the hit reconstruction threshold at the time (MCC7) and a 2 hit requirement for bremsstrahlung photons. Since then, we have better signal processing, improved noise levels, and are developing alternative reconstruction techniques that do not suffer from conventional issues with cosmic contamination at the charge clustering stage (e.g. Wire Cell). We expect this to improve and caution the PAC from concluding that 1 MeV is the lowest detection threshold that is achievable.

Convolutional Neural Networks

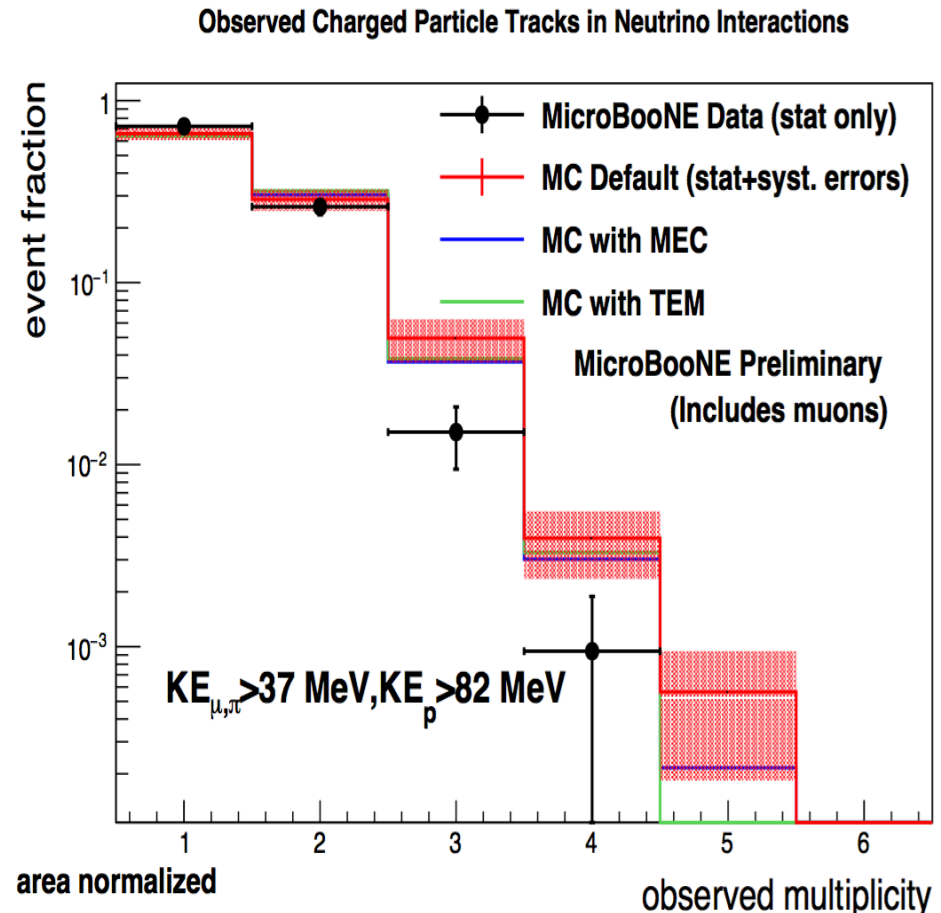
- also exploring more advanced neutrino identification and reconstruction techniques
- first use of convolutional neural networks in the analysis of LAr TPC data
- more to come!

R. Accarri *et al*,
JINST, 12, P03011 (2017)



Charged Track Multiplicity

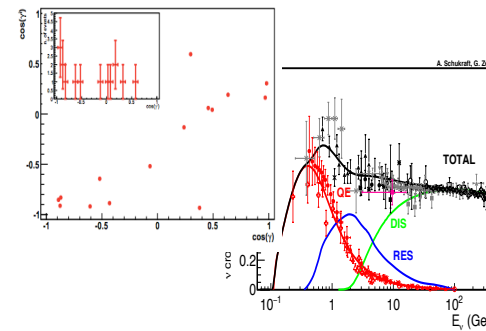
- first measurement of charged track multiplicity in ν_μ CC interactions in argon
- provides a more stringent test of neutrino event generators (*generators can vary widely on final state particle emission*)
- important to understand activity around the ν event vertex if using gaps/topology to identify ν_e events



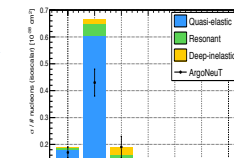
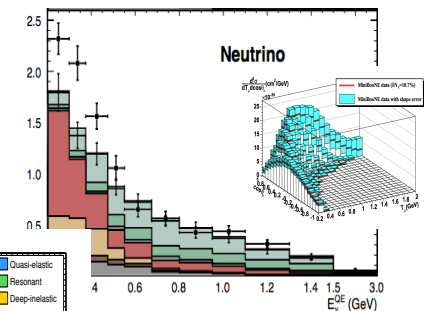
MicroBooNE public note #1024

First physics papers:

- Charged Particle Multiplicity
- $CC\nu\mu$ inclusive xsec
- $CC\pi^0$ xsec
- $CC1p$ xsec
- ...



Results



Energy reconstruction and energy scale calibration

Momentum reconstruction

Particle & event ID

Cosmic removal

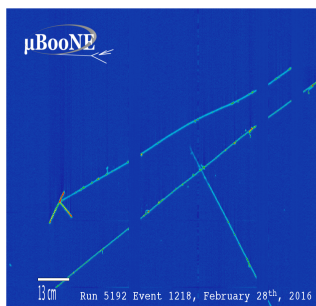
2D & 3D event reconstruction

Noise filtering & signal processing

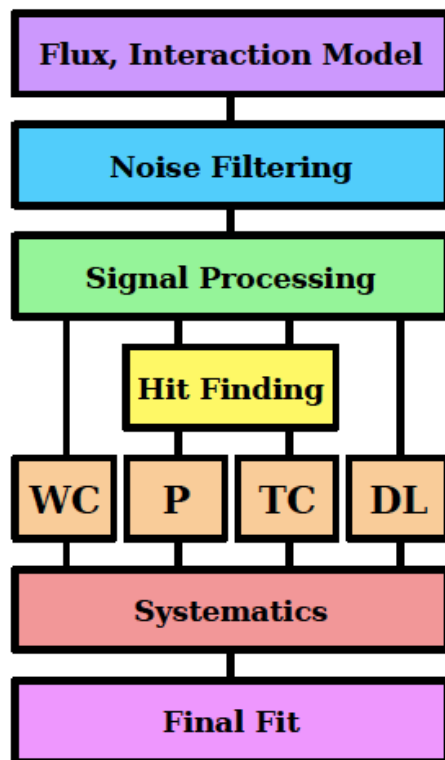
Detector response calibration & simulation

LAr/e propagation properties

Data



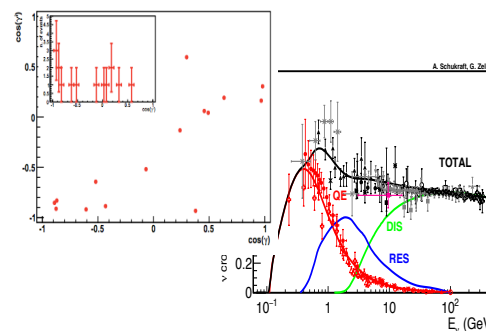
Anne Schukraft
FNAL User's meeting, 2017



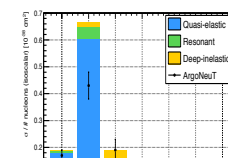
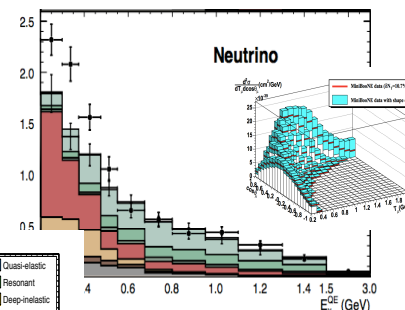
Path to LEE

Four analysis paths presently under development

Shared tools up to signal processing and for systematics and final fit



Results



Energy reconstruction and energy scale calibration

Momentum reconstruction

Particle & event ID

Cosmic removal

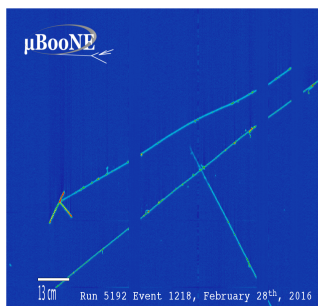
2D & 3D event reconstruction

Noise filtering & signal processing

Detector response calibration & simulation

LAr/e propagation properties

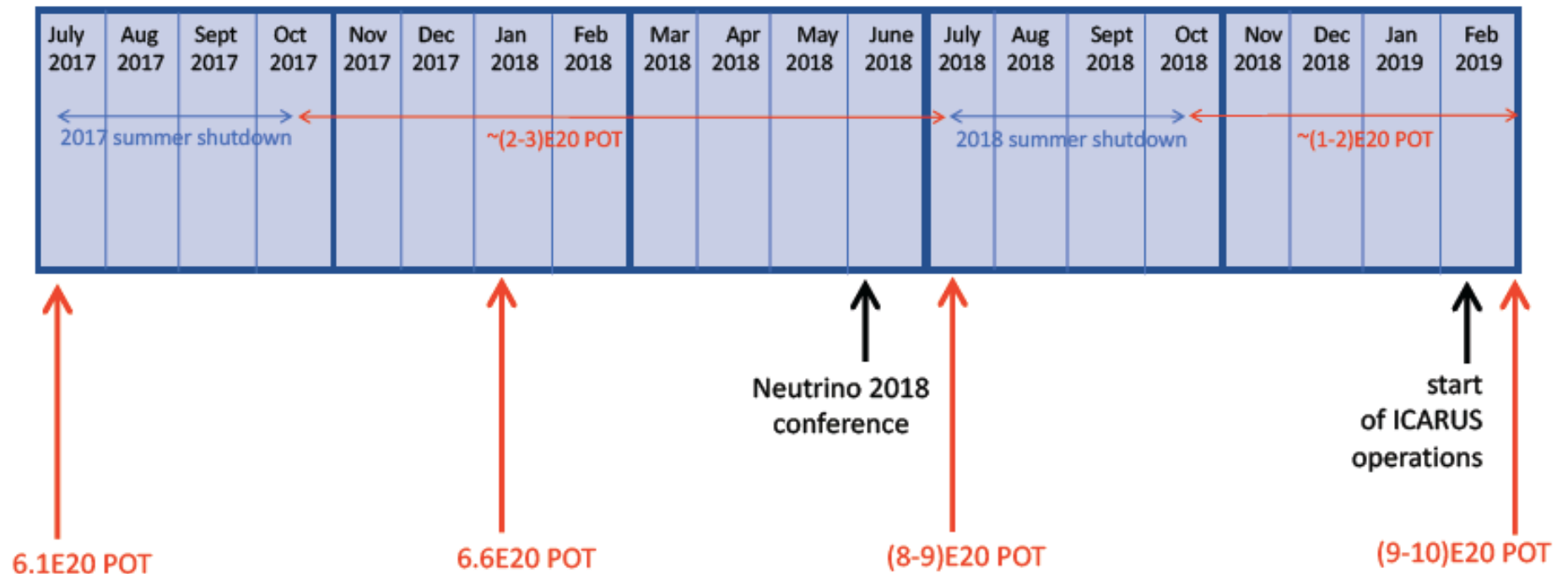
Data



Different paths have different philosophies wrt efficiency, purity, noise processing/calorimetry, ...

Anne Schukraft
FNAL User's meeting, 2017

MicroBooNE Road Map



Postdoc Placement

- 26 of our postdocs have landed their next position
- majority have remained on MicroBooNE (19/26)

(1) Roxanne Guenette, Oxford, STFC Rutherford Fellow → Harvard
(2) David McKee, Missouri Southern State University, Assistant Professor
(3) Mike Cooke, DOE, AAAS Science & Technology Policy Fellow
(4) Teppei Katori, Queen Mary University of London, Lecturer
(5) Georgia Karagiorgi, Manchester, Lecturer → Columbia
(6) Bryce Littlejohn, IIT, Assistant Professor
(7) Tingjun Yang, FNAL, Applications Physicist, ND
(8) Zarko Pavlovic, FNAL, Applications Physicist, ND
(9) Andrzej Szec, Manchester, Lecturer
(10) Eric Church, PNNL, Scientist
(11) Wes Ketchum, FNAL, Associate Scientist, SCD
(12) Andy Blake, Lancaster, Lecturer
(13) Josh Spitz, Michigan, Ann Arbor, Assistant Professor
(14) Thomas Strauss, FNAL, Associate Scientist, TD
(15) Matt Touns, FNAL, Associate Scientist, ND
(16) Jonathan Asaadi, UT Arlington, Assistant Professor
(17) Leonidas Kalousis, Vrije Universiteit Brussel, Research Associate
(18) Anne Schukraft, FNAL, Associate Scientist, ND
(19) Sowjanya Gollapinni, University of Tennessee, Assistant Professor
(20) Roberto Acciarri, FNAL, Applications Physicist, ND
(21) Ben Carls, Excelon
(22) Tia Miceli, Allstate
(23) Mike Mooney, Colorado State, Assistant Professor
(24) Taritree Wongjirad, Tufts, Assistant Professor
(25) Kazu Terao, Research Scientist, SLAC
(25) Yun-Tse Tsai, Research Scientist, SLAC

- 12 University
(5 non-U.S., 7 U.S.)
- 10 U.S. lab
- 1 U.S. government
- 1 second postdoc
- 2 Data Science

Conclusions

Very successful first 18 months of data taking and analysis

- Some downtimes → lessons learned for the community
- Will finish 6.6E20 POT collection during FY2018 (about ½ a year ahead of schedule)
- Ready to start SBN era 6.6E20 – no reason to wait
- Added detector functionality as we go
- 6 papers and 15 public notes already
- Proceeding towards first physics papers and signature results
- Strong collaboration. Young people driving the science and moving on in the field