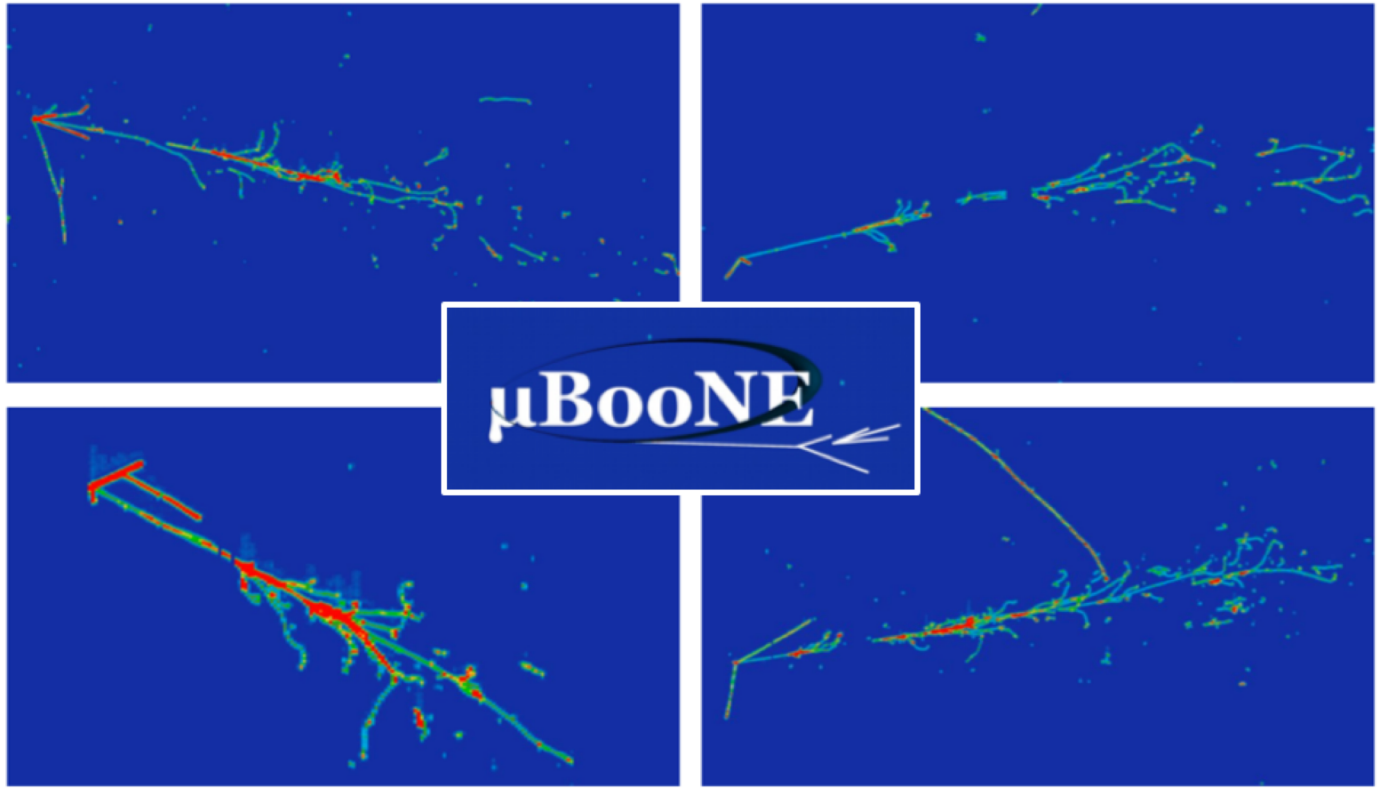
Update from MicroBooNE

Bonnie Fleming, Sam Zeller

Fermilab PAC Meeting

June 7, 2021



MicroBooNE Collaboration

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University of California, Santa Barbara: X. Luo, N. Kaneshige, D. Totani, E. Yandel
University of Cambridge: J. Anthony, S. Dennis, P. Detje, A. Moor, J. Shi, A. Smith, M. Uchida, K. Wresilo
University of Chicago: K. Miller, D.W. Schmitz
CIEMAT: J. Crespo
University of Cincinnati: R.A. Johnson
Colorado State University: D. Carber, I. Caro Terrazas, M. Mooney
Columbia University: L. Camilleri, D. Cianci, G. Ge, Y.-J. Jwa, D. Kalra, G. Karagiorgi, M. Ross-Lonergan, W. Seligman, M. Shaevitz, H. Siegel, K. Sutton
University of Edinburgh: L. Jiaoyang, M. Nebot-Guinot, A.M. Szelc
Fermilab: S. Balasubramanian, S. Berkman, D. Caratelli, F. Cavanna, G. Cerati, M. Del Tutto, K. Duffy, A. Ereditato (joint with Yale), S. Gardiner, E. Gramellini, H. Greenlee, C. James, W. Ketchum, M. Kirby, T. Kobilarcik, T. Mohayai, C. Moore, O. Palamara, Z. Pavlovic, J.L. Raaf, A. Schukraft, E. Snider, M. Stancari, J. St. John, T. Strauss, M. Toups, S. Wolbers, M. Wospakrik, W. Wu, T. Yang, G.P. Zeller*, J, Zennamo
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Illinois Institute of Technology: R. An, R. Dorrill, B. Littlejohn
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Lancaster University: A. Blake, D. Devitt, J. Nowak, N. Patel, I. Pophale, C. Thorpe
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University of Michigan, Ann Arbor: C. Barnes, R. Fitzpatrick, J. Mousseau, J. Spitz
University of Minnesota: R. Diurba, A. Furmanski, C. Hilgenberg
MIT-HEP: J.M. Conrad, N. Kamp, L. Yates
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New Mexico State University: V. Papavassiliou, S.F. Pate, L. Ren, S. Sword-Fehlberg
University of Oxford: G. Barr
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Rutgers: A. Mastbaum, I. Lepetic, K. Lin
SLAC: M. Convery, R. Itay, L. Rochester, K. Terao, Y-T. Tsai, T. Usher
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University of Southern Maine: B. Eberly
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177 collaborators

36 institutions in 5 countries

39 postdocs

60 grad students

37% international students

includes Masters & post-bacc

*spokespeople

MicroBooNE Papers

2017 | 2018 | 2019 | 2020 | 2021

strong track record of papers since 2017

- ~ ½ JINST
- ~ ½ Phys Rev, EPJC

Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector
Design and Construction of the MicroBooNE Cosmic Ray Tagger System
Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
Design and Construction of the MicroBooNE Detector

since the last PAC:

- 12 papers
- 20 public notes

- the investment we made in improving our signal processing, calibrations, event reconstruction, systematics, and neutrino interaction modeling has paid off; we have been sharing this with the community as we go

Detector Physics

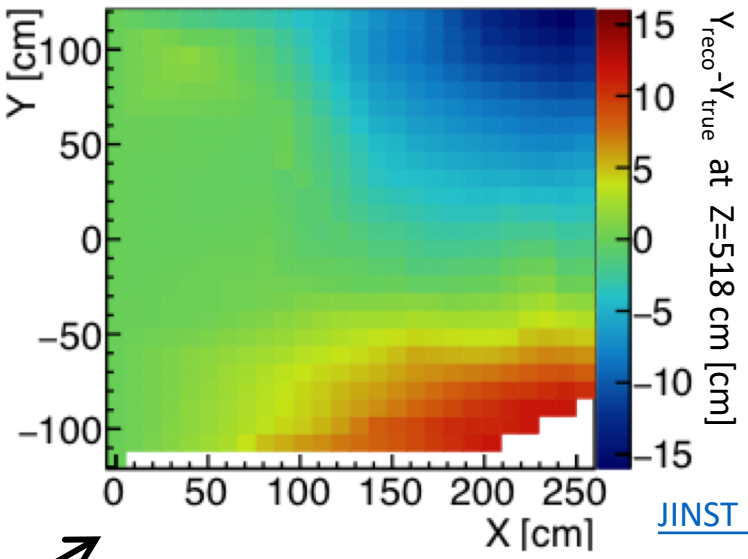
- we have put a lot of work into our detector response model (MCC9)

- advanced signal processing
  - 2D de-convolution, influence of neighboring wires
  - JINST 13, P07006 (2018), JINST 13, P07007 (2018)

- data-driven electric field maps
  - UV laser: JINST 15, P07010 (2020)
  - cosmic muons: JINST 15, P12037 (2020)

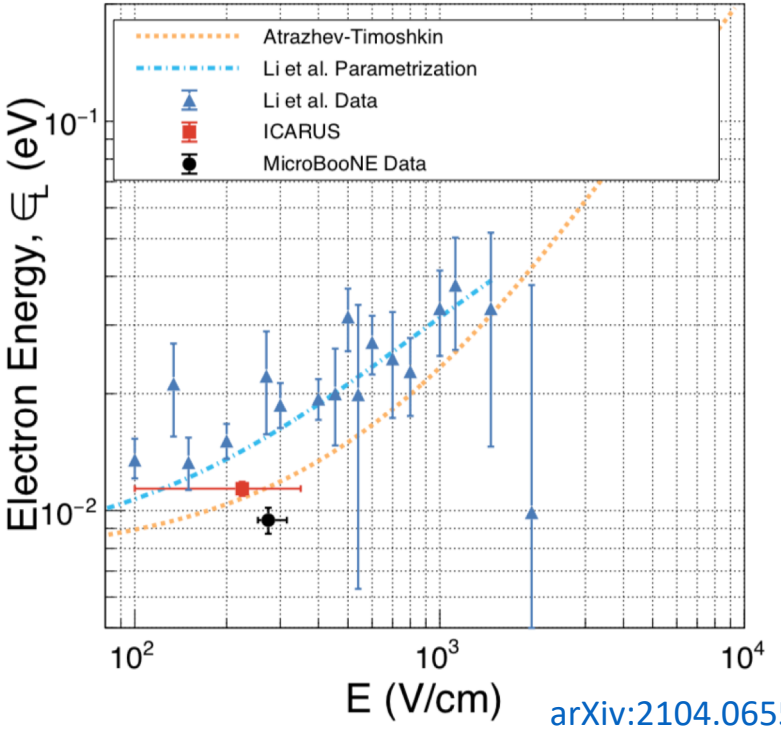
- calorimetric and EM shower calibrations
  - JINST 15 P03022 (2020), JINST 15 P02007 (2020)

- longitudinal diffusion of ionization e^-'s
  - arXiv:2104.06551



← MicroBooNE UV laser calibration data

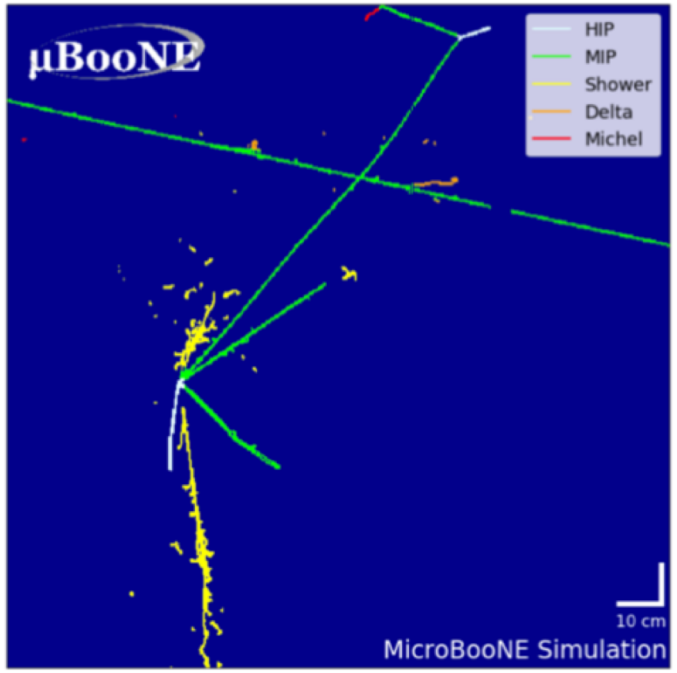
JINST 15, P07010 (2020)



arXiv:2104.06551

Event Reconstruction

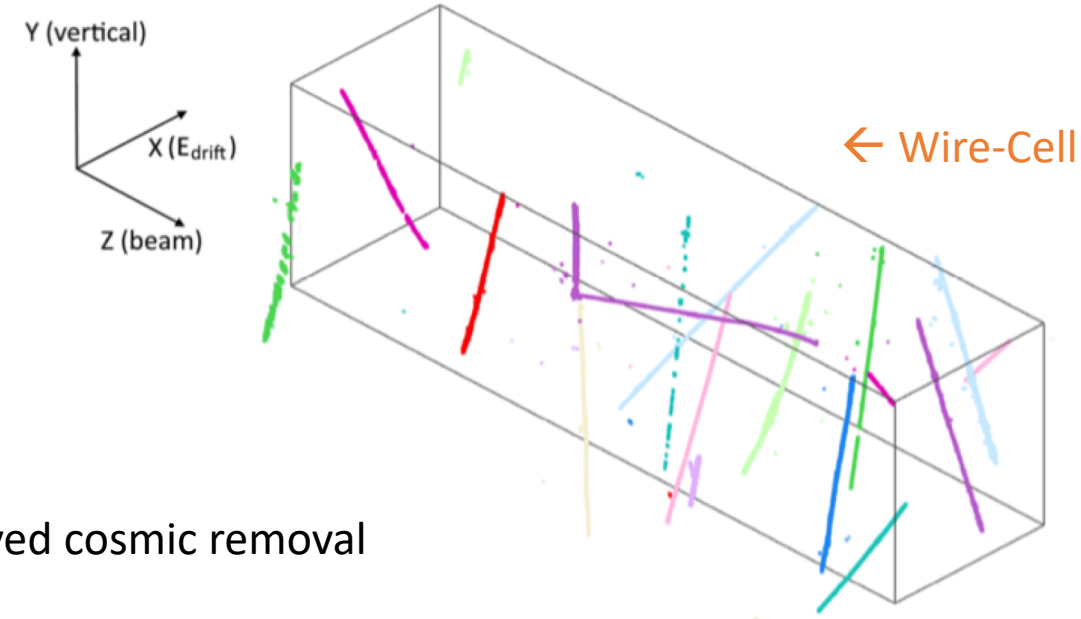
Deep Learning (DL) →



- we have also put a lot of investment into neutrino event reconstruction with multiple independent approaches

- Pandora
  - Eur. Phys. JC78, 82 (2018)
  - multiple neutrino cross section results (CC inclusive, CC π^0, CC Np, QE-like, ν_e) + BSM searches (HNL, Higgs portal scalar)

- Deep Learning (DL)
  - PRD 103, 052012 (2021), PRD 103, 092003 (2021), JINST 16, P02017 (2021), PRD 99, 092001 (2019), JINST 12, P03011 (2017)
  - first of their kind applications in a LAr TPC



← Wire-Cell

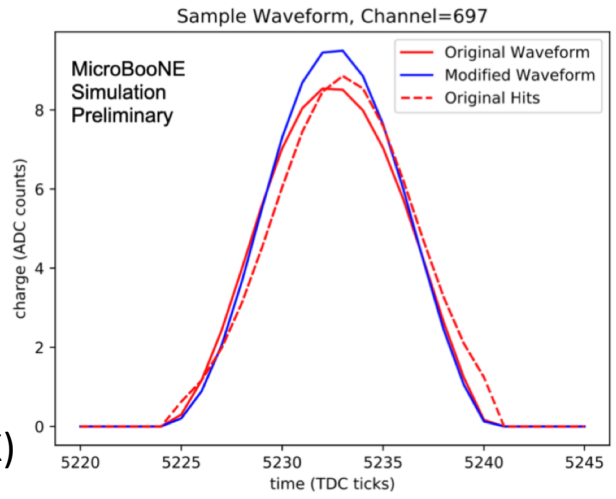
- Wire-Cell
  - arXiv:2101.05076, arXiv:2012.07928 (accepted to PRA), arXiv:2011.01375 (accepted to JINST)
  - fully 3D, next-generation charge-to-light matching, improved cosmic removal

Systematics

- we have produced the first assessment of complete systematics in a LAr TPC, this has been years in the making

- detector uncertainties
  - novel data-driven technique using wire responses
  - has significantly reduced our detector systematics
  - paper in preparation
  - MicroBooNE public note #1075

MicroBooNE public note #1075



- neutrino cross section uncertainties
  - we apply best practices from other experiments (MINERvA, NOvA, T2K)
  - and the results from our own GENIE tuning
  - we vary > 50 different parameters to assess ν interaction uncertainties
  - MicroBooNE public note #1074

Variation Name
genie_all
AGKYpT1pi
AGKYxF1pi
AhtBY
BhtBY_UBGenie
CV1uBY
CV2uBY_UBGenie
CoulombCCQE
EtaNCEL
FrAbs_N_UBGenie
FrAbs_pi
FrCEx_N
FrCEx_pi
FrInel_N_UBGenie
FrInel_pi
FracDelta_CCMEC
FracPN_CCMEC
MFP_N
MFP_pi
MaCCQE
MaCCRES
MaNCEL
MaNCRES
MvCCRES
MvNCRES
NonRESBGvbarnCC1pi
NonRESBGvbarnCC2pi
NonRESBGvbarnNC1pi
NonRESBGvbarnNC2pi
NonRESBGvbarpCC1pi
NonRESBGvbarpCC2pi
NonRESBGvbarpNC1pi
NonRESBGvbarpNC2pi
NonRESBGvnCC1pi
NonRESBGvnCC2pi
NonRESBGvnNC1pi_UBGenie
NonRESBGvnNC2pi_UBGenie
NonRESBGvpCC1pi
NonRESBGvpCC2pi
NonRESBGvpNC1pi
NonRESBGvpNC2pi
Min/Max Variations
NormCCCOH
NormNCCOH
RPA_CCQE
Theta_Delta2Npi
VecFFCCQEshape
AxFFCCQEshape
DecayAngMEC

- neutrino flux uncertainties
  - make use of the very well-understood BNB from MiniBooNE
  - MicroBooNE public note #1031

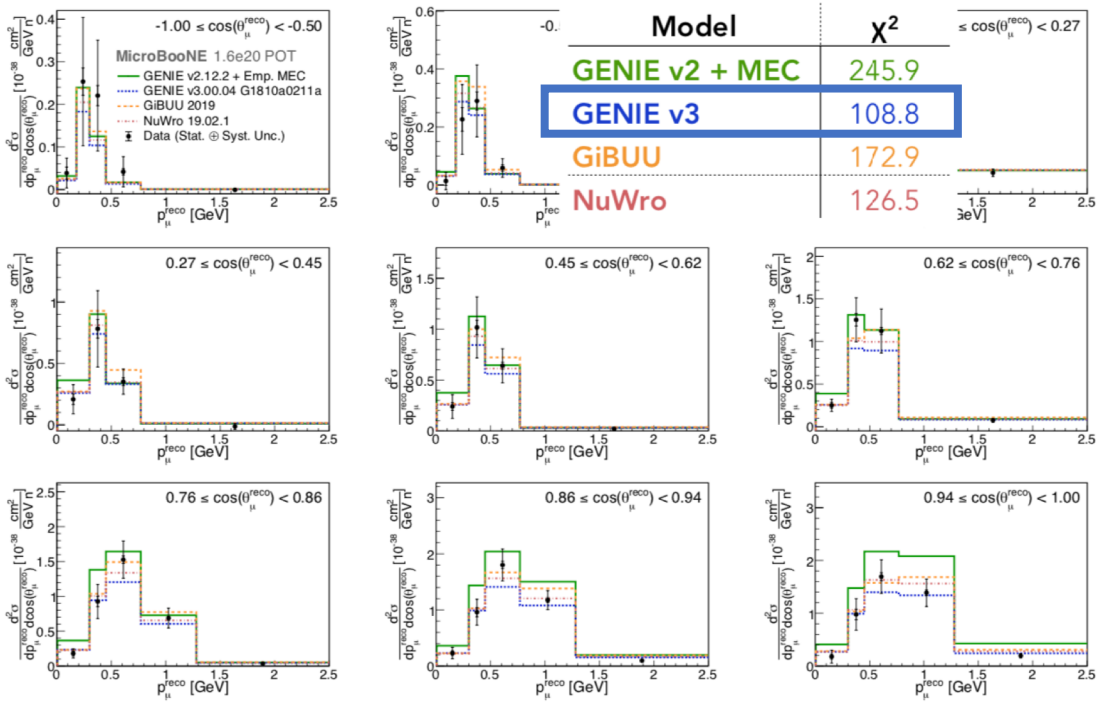
Neutrino Interaction Modeling

- MicroBooNE drove the development of v3 GENIE, what is being called the "most significant upgrade of GENIE in a decade"; this is the result of a 2 year-long effort

- MicroBooNE GENIE tune
  - includes new nuclear models, new fits to global data
  - paper in preparation
  - MicroBooNE public note #1074

- we are the first to examine neutrino scattering in argon at these energies and with such high statistics

- we are also learning a lot from our own data



Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5

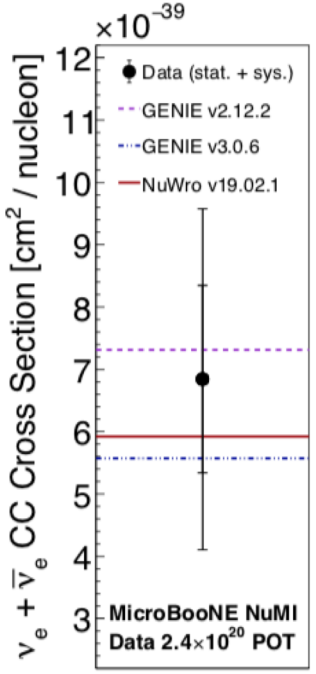
MicroBooNE ν_μ CC inclusive data
PRL 123, 131801 (2019)

Neutrino Cross Sections

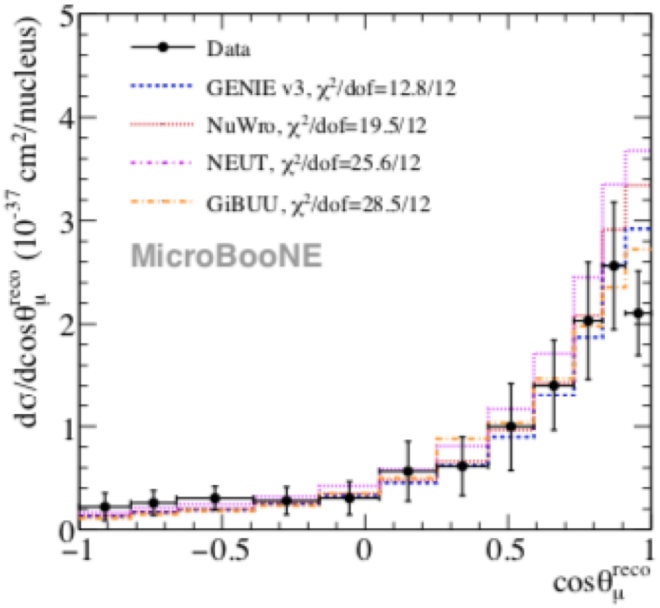
- the large data samples collected have allowed for a very active neutrino cross section program on MicroBooNE; many of these measurements are first + head start for SBND

- ν_e CC inclusive (ν_e + Ar → e + X), from NuMI beam!
  - arXiv:2101.04228 (2021)
- CC Np (ν_μ + Ar → μ + any # protons, no π's) (W&C seminar 2020)
  - PRD 102, 112013 (2020)
- QE-like (ν_μ + Ar → μ + p) (W&C seminar 2020)
  - PRL 125, 201803 (2020)
- ν_μ CC inclusive (ν_μ + Ar → μ + X) (W&C seminar 2019)
  - PRL 123, 131801 (2019)
- charged track multiplicities (W&C seminar 2018)
  - Eur. Phys. J. C79, 248 (2019)
- CC π^0 (ν_μ + Ar → μ + π^0) (W&C seminar 2018)
  - PRD 99, 091102R (2019)

arXiv:2101.04228 (2021)



PRD 102, 112013 (2020)



- more coming soon! updates on the above plus new results on NC elastic, CC 2p, transverse kinematics, NC π^0, CC/NC π^0, CC π^+, CC coherent π^+, kaon and η production

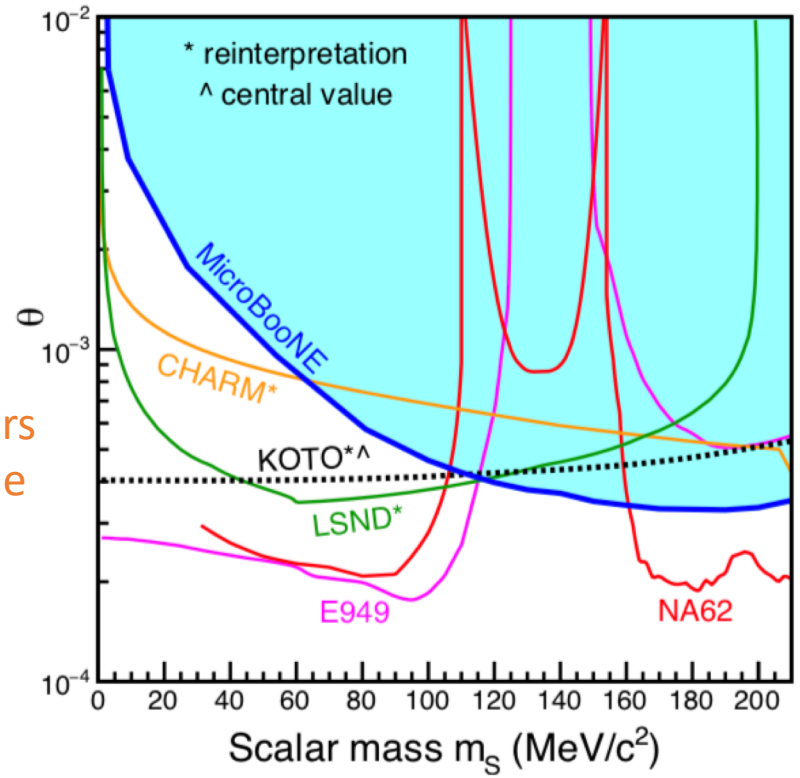
BSM Physics

- we also have a very vibrant astro-particle physics and exotics physics group; note: this is not a wish list, these are all active analyses on MicroBooNE, establishing methods for DUNE

  - Higgs portal scalar (e^+e^- final state)
    - arXiv:2106.00568 (posted last week)
  - supernova burst neutrino readout
    - JINST 16, P02008 (2021)
  - cosmic muon rates
    - JINST 16, P04004 (2021)
  - heavy neutral leptons ($\mu\pi$ final state)
    - PRD 101, 052001 (2020)
    - beam timing improvements
  - MeV scale physics
    - MicroBooNE public note #1076
    - radon injection studies
  - neutron-antineutron oscillations
    - MicroBooNE public note #1093
  - millicharged particle searches
  - dark tridents, dark scalars, dark neutrino models (work with Pascoli, Abdullahi, Hostert)

searching for e^+e^- pairs using events from the NuMI beam in MicroBooNE →

arXiv:2106.00568



MicroBooNE's Examination of the MiniBooNE Low Energy Excess (LEE)

MicroBooNE's Job

- to be responsive to how the theoretical and experimental landscape has evolved wrt the MiniBooNE low energy excess

- leverage as much of the LAr TPC technology as we can
  - *the LAr TPC technology opens up more information and more final state channels than were available in a Cerenkov detector such as MiniBooNE*
  - *we are doing more than repeating MiniBooNE with a few different reconstructions*
  - *if an excess is seen in MicroBooNE, we want to be able characterize that excess beyond simply whether it is electrons or photons but also in terms of particle content and kinematics (on both the leptonic and hadronic side)*

- you'll see this reflected in our upcoming strategy for bringing out MicroBooNE results ...

MicroBooNE's Short-Baseline Journey

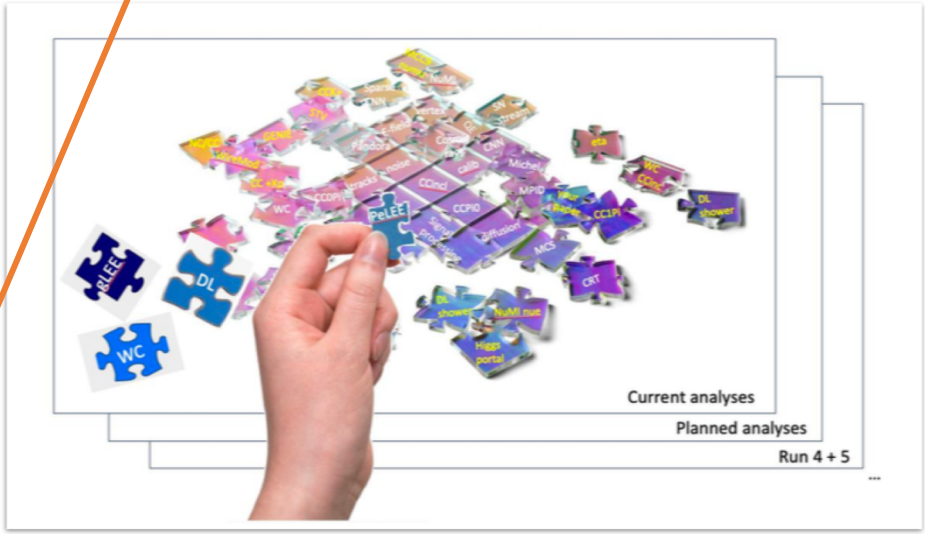
we will be addressing a series of questions in a series of steps …

- what if we take an initial look at a MiniBooNE-like final state 1e0π? (1eNp, 1e0p)
- what if we measure Delta radiative decays, leading photon-based explanation for MiniBooNE? (1γ1p, 1γ0p)
- what if we zone in on quasi-elastic events with 2-body kinematics and high purity? (1e1p)
- what if we examine more inclusive hadronic final states and with higher efficiency? (1eX)

- what if we examine more inclusive final states with a photon? (1γX)
- what if add in a muon neutrino disappearance search? (1μ1p)
- what if we include more complex leptonic final states e^+e^-?
  → we do not want to be restricted to only single e^- final states
- what if we add more data? we have a x2 more data to process
- what if we do a combined BNB + NuMI analysis in MicroBooNE?
- what happens when we also add in ICARUS and SBND?

… highlights our unique capabilities

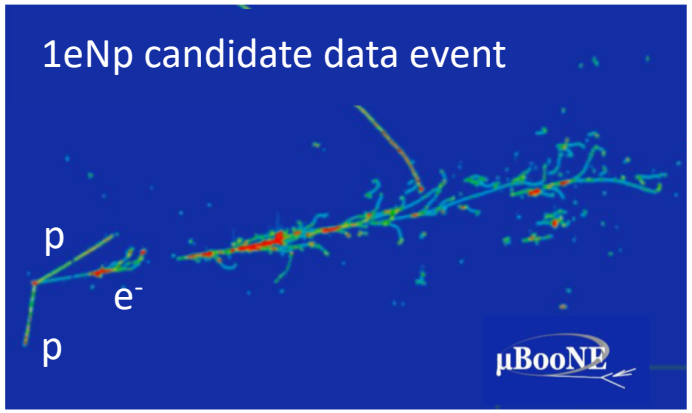
the first wave

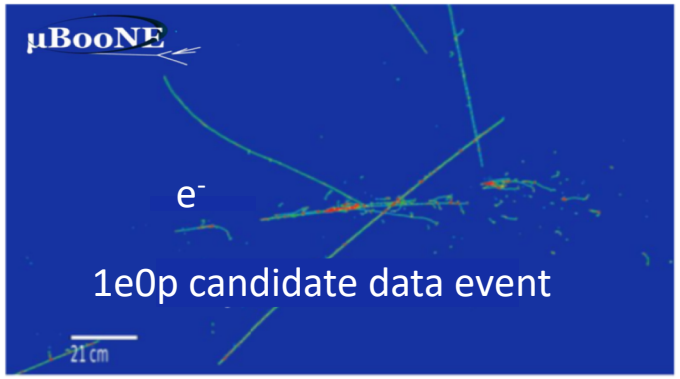


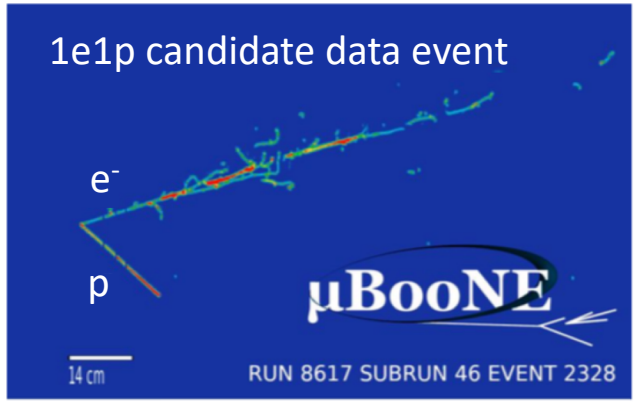
what did MiniBooNE see?

First Series of Results

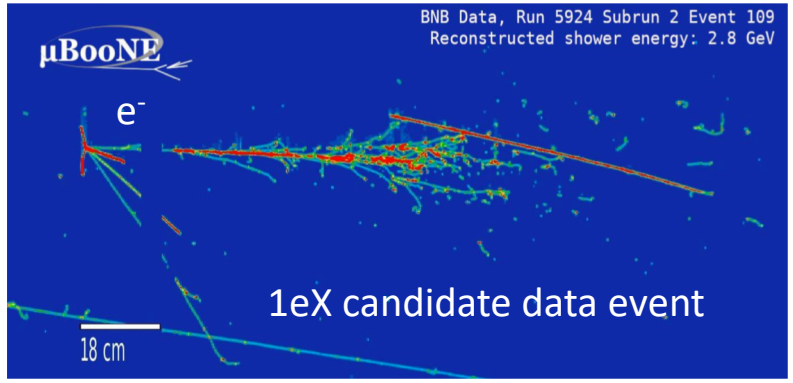
- ν_e analyses
  - MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
  - restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
  - all ν_e final states (Wire-Cell, 1eX)
- single photon analysis
  - targeting Delta radiative decay hypothesis (Pandora, 1γ1p, 1γ0p)

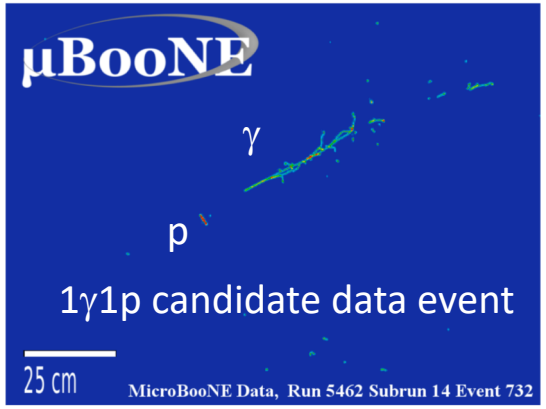


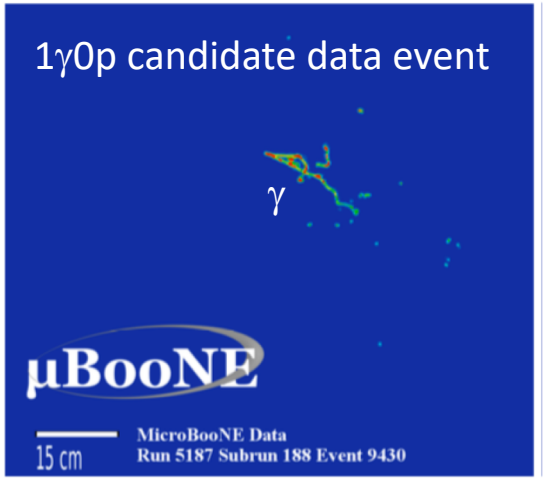




- 4 analyses, 6 final states







First Series of Results

- ν_e analyses
  - MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
  - restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
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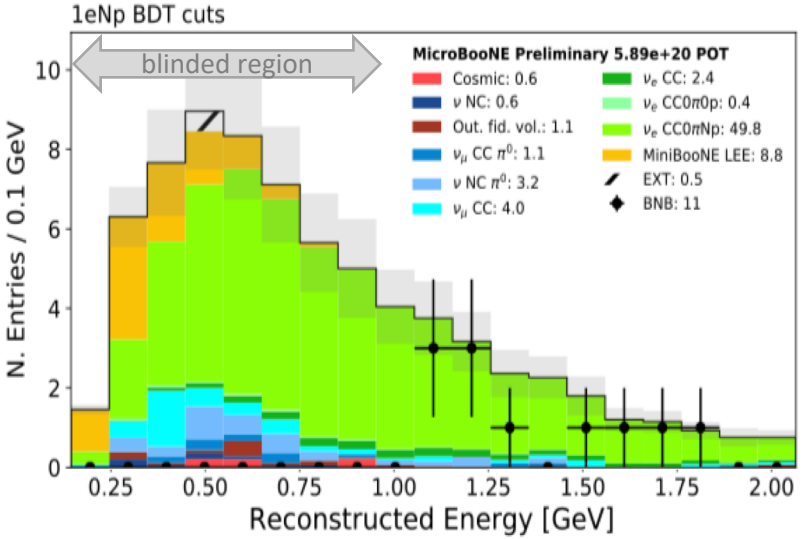
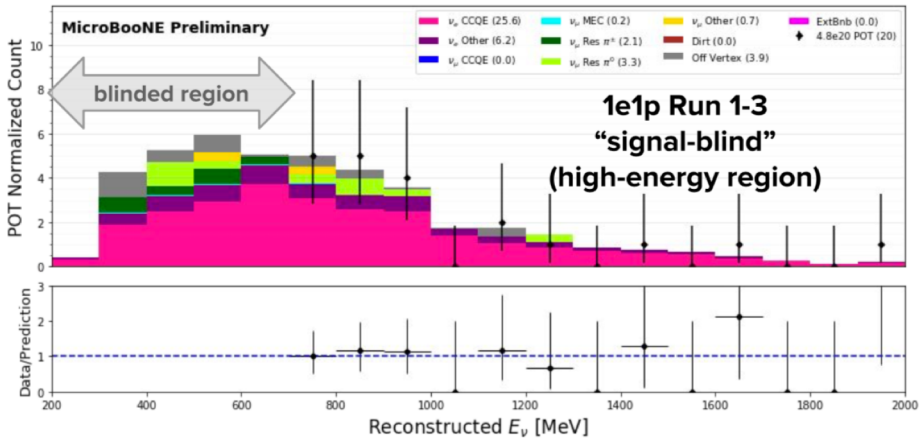
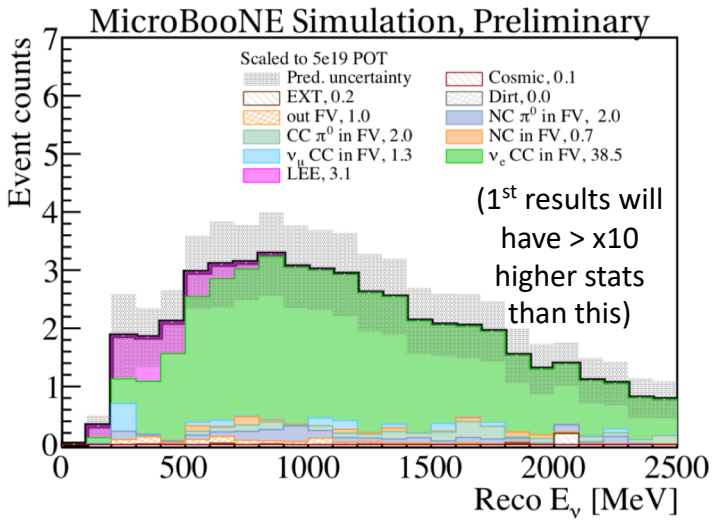
- single photon analysis
  - targeting Delta radiative decay hypothesis (Pandora, 1γ1p, 1γ0p)



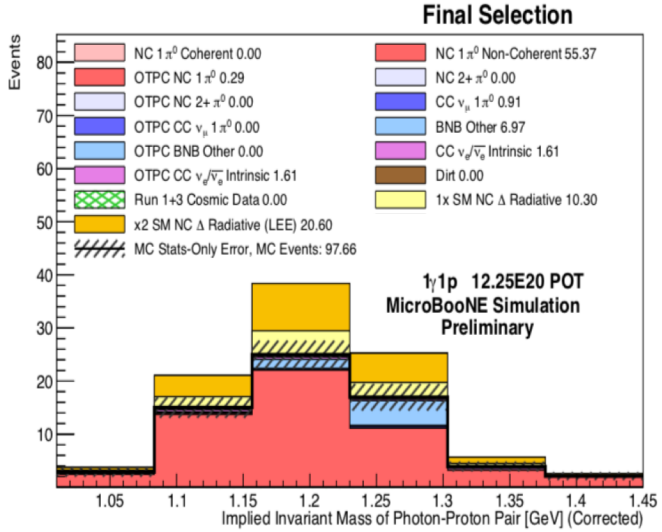
MicroBooNE public note #1085



MicroBooNE public note #1086



MicroBooNE public note #1095



MicroBooNE public note #1087

First Series of Results

- ν_e analyses
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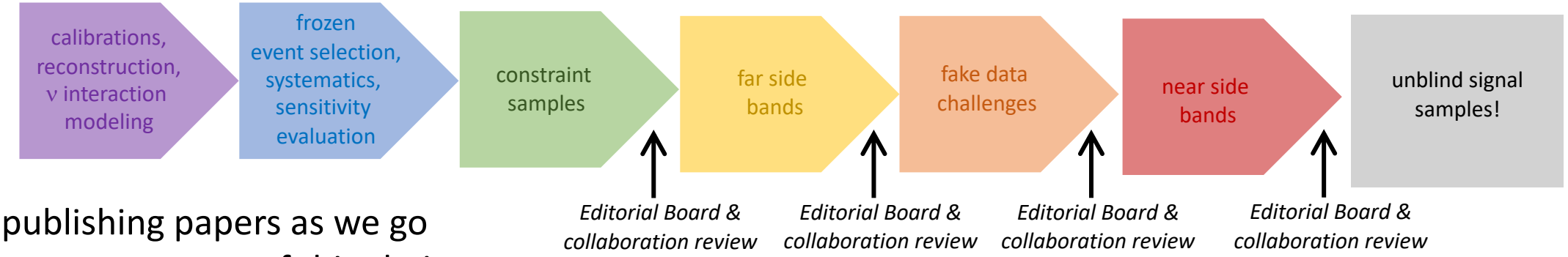
  - all ν_e final states (Wire-Cell, 1eX)
- single photon analysis
  - targeting Delta radiative decay hypothesis (Pandora, 1γ1p, 1γ0p)

- first wave will include 1 photon + 3 electron analyses
  - *6 final states*
  - *+ ν_μ CC and π^0 constraints*
- each will use 1/2 of the MicroBooNE data set
- these analyses are presently in very advanced stages

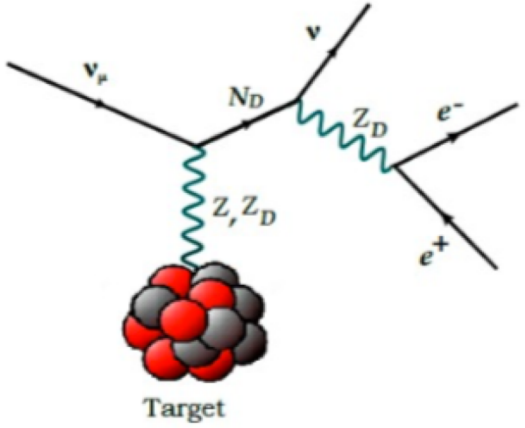


stay tuned!

publishing papers as we go on components of this chain

Rich and Evolving Theory Landscape

- in part, this has been motivated by attempts to explain SBL anomalies; ex., ν_e appearance but no ν_μ disappearance



Bertuzzo *et al.*, PRL 121, 241801 (2018)

- dark tridents, dark scalars, dark neutrinos
  - *Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *Abdullahi, Hostert, Pascoli, arXiv:2007.11813*
  - *Alvarez-Ruso, Saul-Sala, arXiv:1705.00353*
- heavy sterile neutrinos, heavy neutral leptons
  - *Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *Gninenko, PRD 83, 093010 (2011)*
- more complex Higgs physics
  - *Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
  - *Abdallah, Gandhi, Roy, arXiv:2010.06159*
- mixed models of neutrino oscillations and decay
  - *Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
  - *Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- axion-like particles
  - *Chang, Chen, Ho, Tseng, arXiv:2102.05012*
- new particles produced in the beam
  - *Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

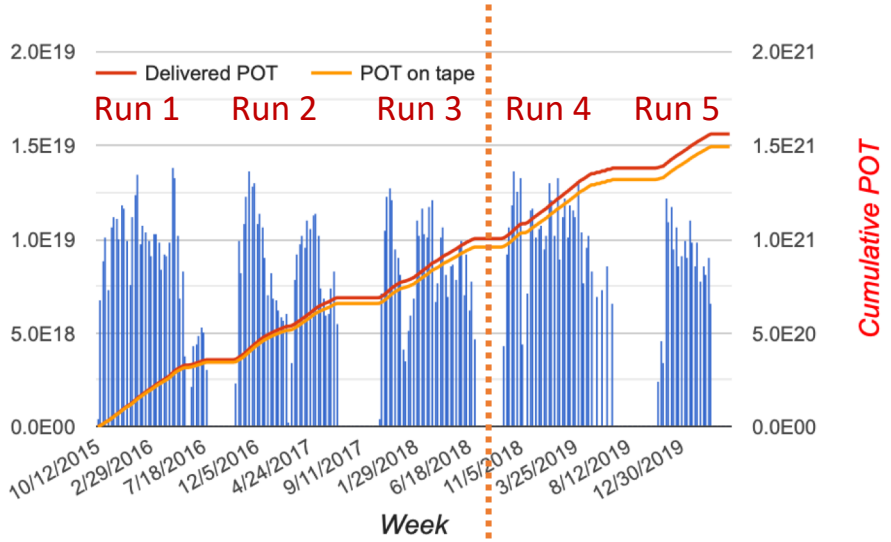
(caution: not an exhaustive list)

- many of these models predict more complex final states (e^+e^-) & differing levels of hadronic activity
- want a more agnostic approach than solely testing a sterile neutrino hypothesis ($1e^- + X$)
- we are fortunate that LAr TPCs are sensitive to these possibilities

MicroBooNE's Exploration of the MiniBooNE Excess

first series of results (1/2 the MicroBooNE data set)	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^- + X	$1\gamma 0p$	$1\gamma p$	$1\gamma X$
sterile ν	✔	✔	✔	✔					
Higgs physics		✔	✔	✔		✔			
dark ν	✔				✔				
Z' boson	✔				✔				
axion-like particles	✔				✔				
sterile ν + decay							✔		
heavy sterile ν							✔		
SM γ production							✔	✔	✔
???	✔	✔	✔	✔	✔	✔	✔	✔	✔

MicroBooNE R&D Program



- we completed 5 years of high quality ν data-taking and have since been working to execute our R&D program aimed at not leaving outstanding mysteries from μB
- R&D line-up includes understanding:
  - what is the cause of the last un-explained noise source in MicroBooNE
    - *MicroBooNE noise characterization paper: JINST 12, P08003 (2017)*
  - why are we seeing such a high single photo-electron rate in the detector
    - *single photo-electron rates as a function of drift HV and with reverse cathode polarity, argon assay at CIEMAT*
  - are we able to operate at design high voltage
    - *raise the drift HV to design (70 kV → 128 kV)*
  - what is the impact of various UV laser grounding schemes for DUNE
  - are there real-time triggering solutions that can get physics faster in SBND, DUNE ND
  - what is the impact of doping the argon?

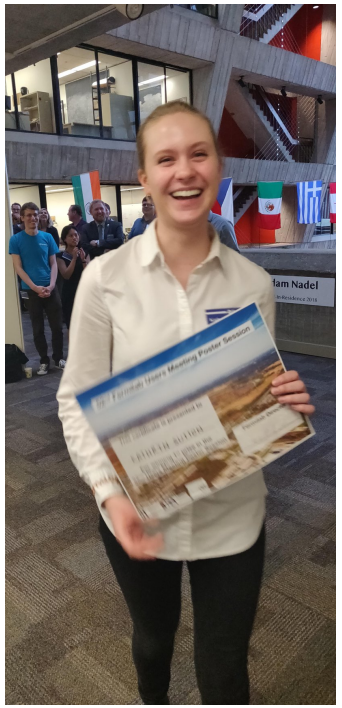
MicroBooNE Computing

- we have completed a major baselining, the first of its kind for a LAr TPC, with very large data and Monte Carlo sets and a full suite of systematics
- we want to analyze the full 5 years of BNB + NuMI ν data that we have collected (we have processed ½ of this)
  - *in consultation with Jim Amundson, we are working with SCD on how best to optimize this*
- we will continue to provide detailed multi-year projections of our computing needs at the annual FCGSR reviews, this has worked well for us
- we have worked to be good citizens and to delete older data and Monte Carlo campaigns
  - *deleted all past productions (MCC1-7) + are discussing with SCD how long we should keep samples post publication*
  - *planning one more campaign MCC10 whose scope/scale is TBD, currently under discussion in MicroBooNE*

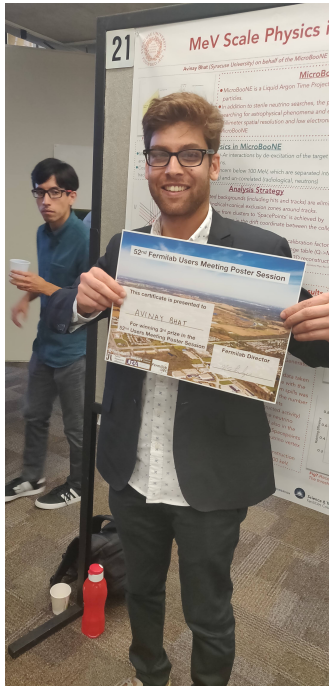
	2020 (actual)	2021	2022	2023
cumulative data storage needs (PB)	4.9	3.5	3.5	3.5
grid computing needs (M CPU-Hr)	54	30	30	30

Award-Winning MicroBooNE Students

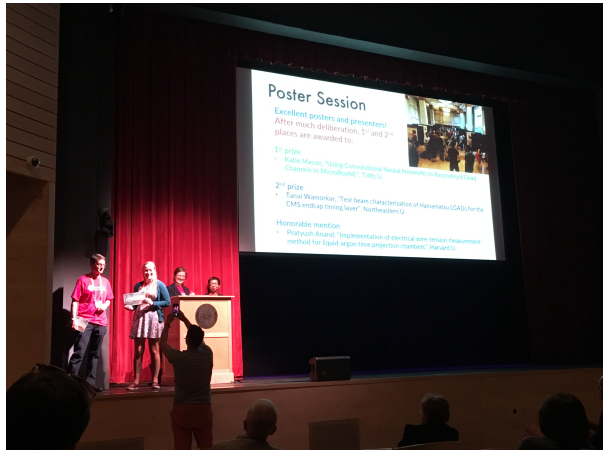
a few examples



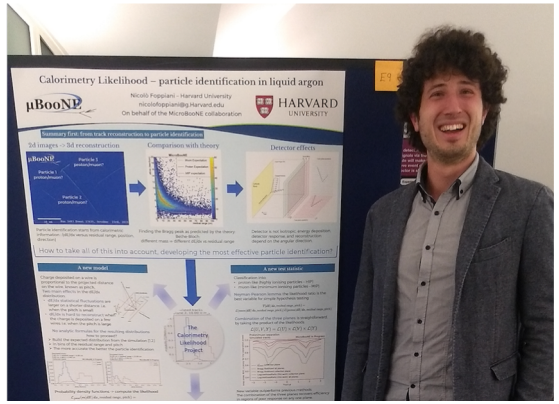
Kathryn Sutton (Columbia)
1st place FNAL Users Meeting
Searching for $\Delta \rightarrow N\gamma$ in MicroBooNE
June 2019



Avinay Bhat (Syracuse)
3rd place FNAL Users Meeting
MeV Scale Physics in MicroBooNE
June 2019



Katie Mason (Tufts)
1st place DPF poster contest
Using Infill Networks for MicroBooNE Data Analysis
July 2019

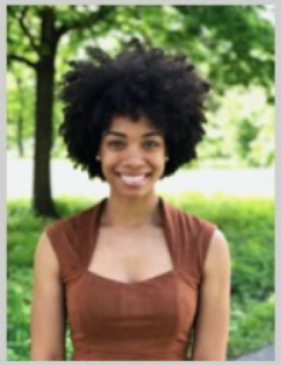


Nicolo Foppiani (Harvard)
experimental poster prize, NuPhys 2019
Particle Identification in MicroBooNE
December 2019

Vincent Basque (Manchester)
1st place INSS poster contest
Scintillation Light Triggering in MicroBooNE
August 2019

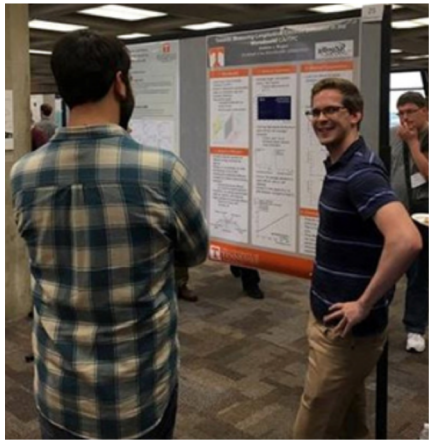
Andrew Mogan (UTK)
1st place FNAL Users Meeting
Constraining NC π^0 Backgrounds for MicroBooNE's $\Delta \rightarrow N\gamma$ Search
August 2020

#BlackInPhysics 3MT Competition Winners



1st Place
Katrina Miller
University of Chicago

Katrina Miller (Chicago)
1st place, 3-minute thesis competition
Measuring ν_e Cross Sections Using NuMI Data in MicroBooNE
November 2020



Summary

- We have built what is now (arguably) the most sophisticated and advanced simulation for liquid argon TPCs. We've come a very long way.
  - *pioneering signal processing and charge/light matching*
  - *full detector calibrations*
  - *first complete assessment of systematics in liquid argon*
  - *multiple fully-automated event reconstruction paradigms*
  - *significant nuclear model upgrades to GENIE*
- We are laying a careful foundation. We are pioneers in many aspects. We have a strong team. We are publishing a lot.
  - *MicroBooNE had a record year of publications*
- A series of first results on the MiniBooNE low energy excess are around the corner. The short-baseline anomaly landscape has evolved. MicroBooNE is poised to explore this landscape using the full capabilities of LAr TPCs.